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TECHNICAL REPORT
TR-2319-ENV

**REDUCTION OF NOISE FROM THE J-52
AND F-404 JET ENGINES DURING
STATIC TESTING USING THE NOISE
ATTENUATION DEVICE (NAD)**

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EXECUTIVE SUMMARY

The NAD is the Noise Attenuation Device. It is based on results of sub-scale testing undertaken for a Strategic Environmental Research and Development Project (SERDP) and Navy Environmental SDI co-sponsored project “Reduction of Particulate Emissions from Jet Engine Test Cells (JETCs) Using an Annular After-Reactor (AAR).” Those sub-scale tests demonstrated the scientific and engineering basis of the AAR for reducing both particulate matter and nitrogen oxide emissions from a jet engine. They also provided the basis for using the concept of the AAR to reduce jet engine noise. Therefore the full-scale NAD was designed, specifically, for its application to the Navy’s F-414 jet engine, a cornerstone Navy engine. Milestones leading to this application were: (a) test the NAD on the non-after-burning J-52 engine, and (b) evaluate it with the after-burning F-404 engine. Those two milestones have been completed and the results are reported here. Testing of the NAD with the F-414 engine has been approved and is planned for an ESTCP-funded project.

Extrapolation of the sub-scale test results to a full-scale NAD design was accomplished, mainly, with the use of computational fluid dynamics (CFD) analysis of the gas flows through the NAD. These full-scale test results demonstrated that NAD performance exceeded its design objectives by reducing jet exhaust noise levels by more than 20. dBA over a frequency spectrum from 6 – 20,000 Hertz. The NAD is low-cost, transportable, and structurally reliable in an extremely demanding test environment. These tests demonstrated that the NAD met all test criteria for proceeding with testing with the F-414 engine.

The NAD was designed at NAVFAC ESC and fabricated in Southern California. It is of variable diameter (6 feet – 14 feet), 52 feet in length, and weighs 25 tons. It was fabricated in such a way that it could be transported on two truck trailers across country to the Naval Air Weapons Station at Patuxent River MD (NAWC PR) for verification testing at the Outdoor Engine Test Facility (OETF) there. This transportability is a feature that also serves the NADs projected usefulness to the DoD. NAD tests with the J-52 engine showed increasing noise attenuation with engine power, reaching a maximum of 13.5 dBA attenuation at 80% military power. A major problem arose in those tests, however, in that significant engine exhaust was re-ingested into the engine so that the NAD could not be tested at full military power using the cone end-piece. Other than re-ingestion, the results were promising and plans were formulated for further testing of the NAD with the F-404 engine.

An exhaust deflector was designed and fabricated, and the NAD was returned to Southern California for trial assembly of the deflector with the main body of the NAD. The NAD, with deflector, was then returned to NAWC PR for testing with the F-404 engine. Those tests were completed in the fall of 2006 at engine power levels up to, and including, maximum after-burner. The problem of exhaust re-ingestion was resolved; the NAD held together at A/B conditions; near- and far-field noise attenuations of > 20 dBA were recorded over frequencies extending from 6 to 20,000 Hz; operating cost for the NAD was shown to be vanishingly small; the capital investment for fabricating the NAD was small (\$250.k) in comparison to \$14.M required for a Jet Engine Test Cell (JETC - a fully-enclosed facility traditionally used for the static testing of jet engines); and the NADs transportability was demonstrated.

The NAD, to date, has met or exceeded all project objectives set for it. It remains to be demonstrated with the F-414 engine. Upon completion of that test it will also be considered for verification testing and application to other DoD engines and for taking its place as a tool, in addition to Jet Engine Test Cells (JETCs), for reducing noise at DoD aircraft facilities.

TABLE OF CONTENTS

	<u>Page</u>
1.0 INTRODUCTION.....	1
1.1 Background.....	1
1.2 Project Objectives	2
1.3 Regulatory Drivers.....	2
1.4 Stakeholder/End User Issues.....	2
2.0 TECHNOLOGY DESCRIPTION.....	6
2.1 Technology Development and Application	6
2.2 Sub- and Small-Scale Development of NAD Technology	10
2.3 Advantages and Limitations of the NAD Technology	12
3.0 DESIGN OF DEMONSTRATION FIELD TEST	13
3.1 Demonstration Test Objectives	13
3.2 CFD Modeling and Design Basis for Full-Scale NAD	14
3.3 NAD Fabrication.....	20
3.4 Test Planning	20
3.4.1 Selecting Test Sites/Facilities	20
3.4.2 NAD Installation.....	25
3.4.3 Noise Monitoring and Instrumentation Plans	34
3.4.4 Scheduling and Performing Test Operations	37
3.4.5 Operating Parameters for the Technology	37
3.5 Project Management and Staffing.....	38
4.0 FIELD TEST RESULTS.....	40
4.1 Field Test Results for the J-52 Engine.....	40
4.1.1 Results of Noise Measurements.....	40
4.1.2 Exhaust Flow Recirculation To Engine Inlet.....	45
4.2 Field Test Results for the F-404 Engine	45
4.2.1 CFD Analysis, Design and Installation of Flow Deflector	45
4.2.2 F-404 Field Test Noise Measurements	49
4.2.2.1 Near- and Far-Field Noise Insertion Losses	49
4.2.2.2 Background Noise measurements.....	49
4.2.2.3 Near- and Far-Field Noise Spectrums.....	53
4.2.2.4 Effect of Atmospheric Conditions on Far-Field measurements	53
4.2.3 Flow Deflector and F-404 Engine Test Results.....	55
4.3 Test Summaries and Conclusions	55
4.3.1 Test Results From the J-52 Engine	55
4.3.2 Test Results From the F-404 Engine	55
5.0 TECHNOLOGY INTEGRATION	56
5.1 Costs.....	56
5.1.1 Fabrication Costs	56
5.1.2 Activity Costs.....	56
5.1.3 Cost Analysis	57
5.1.4 Life-Cycle Costs	58
5.2 Regulatory Issues	58

TABLE OF CONTENTS (continued)

	5.3 Potential End-Users	<u>Page</u> 59
6.0	CONCLUSIONS	60
7.0	REFERENCES.....	60

APPENDIX

A	Test Procedures for Testing NAD with DoD Low-By-Pass Jet Engines.....	A-1
B	Analytical Methods Supporting the Experimental Design	B-1
C	Health and Safety Plan.....	C-1

LIST OF TABLES

Table 1.1	DoD Aircraft/Engines Having Potential for Application of NAD.....	4
Table 2.1	Inventory of Navy Aircraft / Engine Acoustical Facilities	12
Table 3.1	Project Staffing Relationships.....	39
Table 4.1	Observed Re-circulation of NAD Exhaust Gases to J-52 Engine During Field Testing of NAD Configurations a, b, and c	44
Table 4.2	J-52 NAD Test – Background Noise Data.....	51
Table 4.3	F-404 Baseline Background Noise Data – Aug. 18, 2006.....	52
Table 4.4	F-404 NAD Cone-Open Background – Aug. 16, 2006 (Meter Lower Limit Setting: 55 dB)	52
Table 5.1	NAD Activity Costs.....	57
Table 5.2	JETC Activity Costs	58

LIST OF FIGURES

Figure 1.1	NAD Installation, Including Flow Deflector, with F-404 Engine	5
Figure 2.1	Directional Flows in NAD	7
Figure 2.2	(a) Full Blockage for J-52 Engine Testing, and (b) Partial blockage for F-404	8
Figure 2.3	Strouhal Number and Determination of FPNP	8
Figure 2.4	CFD Modeling Domain	9
Figure 2.5	Sub-Scale 1-1/2 inch Simulated Engine and AAR for Noise Testing	10
Figure 2.6	4-inch Diameter Target Drone Engine with AAR for Noise Testing	10
Figure 2.7	Noise Measurement Results.....	11
Figure 2.8	Construction History of Navy Aircraft /Engine Acoustical Facilities	13
Figure 3.1	Schematic and Design Objectives of Full-Scale NAD, Constructed on Two Skids, for Noise Attenuation of the F-414 Engine	14
Figure 3.2	Parameters Used in Initial Conceptual CFD Study for NAD	16
Figure 3.3	Initial CFD Results Illustrating Minimum Needed Length for NAD	17

LIST OF FIGURES (continued)

	<u>Page</u>
Figure 3.4 Calculated NAD Velocity Flow Field Results for F-414 Engine at After-Burner Without Flow Deflector	17
Figure 3.5 Calculated NAD Mach Number, Pressure, and Temperature Results for F-414 Engine at After-Burner Without Flow Deflector.....	18
Figure 3.6 (a) Longitudinal Section, and (b) Detail of Support Structure of NAD.....	19
Figure 3.7 Internal Features of NAD.....	20
Figure 3.8 NAD During Fabrication at GE-EER Plant in Santa Ana, California	21
Figure 3.9 Exhaust Deflector Being Trial Assembled With NAD at GE-EER Site.....	21
Figure 3.10 Rear View of NAD Assembled With Exhaust Deflector at GE-EER Test Facility.....	22
Figure 3.11 Overhead View of OETF at NAWC PR With Engine and NAD Positions Indicated.....	23
Figure 3.12 Ground-level View of OETF at NAWC PR	23
Figure 3.13 Area Surrounding NAWC PR Showing OETF and Far-Field Noise Measurement Locations	24
Figure 3.14 NAD Installed for Testing With J-52 Engine – No Flow Deflector	24
Figure 3.15 Crane Lifting Forward Section of NAD into Place.....	26
Figure 3.16 Crane Lifting Aft Section of NAD into Place.....	26
Figure 3.17 View Showing Bolted Sections of NAD, Reinforcing Elements, Thrust Turnbuckle, and Tie-Down Chains	27
Figure 3.18 Moving Exhaust Cone (NADc) into Place for Attaching to NADc.....	27
Figure 3.19 NADc “Cone” End-Piece Being Inserted into NAD for Attachment	28
Figure 3.20 Alternative NADa “Grill” End-Piece Attached to NADa.....	28
Figure 3.21 Internal View of Attached “Grill” (NADa) End-Piece	29
Figure 3.22 Internal View of “Grill With Plates” (NADb) End-Piece.....	29
Figure 3.23 A Job Well-Done. After Allowing NAD to Cool From Previous Engine Run, “Plates” Were Installed in ¾ Hour Saving Critical Engine Test Time	30
Figure 3.24 Installed Temperature, Pressure, and Vibration Measurement Cables	30
Figure 3.25 Making Final Adjustments on J-52 Engine Installation.....	31
Figure 3.26 J-52 Engine Ready for Testing.....	31
Figure 3.27 Engine Operating Team Prior to J-52 Test	32
Figure 3.28 Engine Operating Team After J-52 Test	32
Figure 3.29 (a) Making Final Hook-Up for F-404 Engine Test, and (b) Video Recording for TV	33
Figure 3.30 Diagram of Near-Field Noise Measurement Locations at OETF	35
Figure 3.31 Accelerometer, Thermocouple, and Pressure Monitoring Sensors on Both Inner and Outer NAD Shells	35
Figure 3.32 Photograph Showing Berm and Elevated Microphones (a) Single Stationary Microphone at 90’ (right); and (b) Roving and Stationary Microphones at 180’ (left)	36
Figure 3.33 Noise Monitoring Test Team Prior to Dispersing to Far-Field Noise Monitoring Sites	36
Figure 3.34 Working Hard at a Far-Field Noise Monitoring Site	37

LIST OF FIGURES (continued)

	<u>Page</u>
Figure 4.1 Near-Field Sound Pressure Measurements for NADa and NADb Configurations at Military Power	42
Figure 4.2 Near-Field Sound Pressure Measurements for NADb and NADc Configurations at 85% Power	42
Figure 4.3 Noise Insertion Losses for NADb and NADc Configurations for J-52 Engine Operating at 85% power	43
Figure 4.4 Results of Far-Field Noise Measurements at Solomons Island (2 miles distant) with/without NADa for J-52 Engine	43
Figure 4.5 Near-Field Noise Spectrum for J-52 Engine Operating at Military Power With/Without NAD for Baseline and with NADa and NADb Configurations.....	44
Figure 4.6 Far-Field Noise Spectrum for J-52 Engine Operating at Military Power With/Without NAD for Baseline and NADa and NADb Configurations.....	45
Figure 4.7 NAD/Flow Deflector CFD Results	46
Figure 4.8 Outline Drawing of Flow Deflector; (a) Top Central Piece; and (b) Two Side Lower Pieces for Field Installation	48
Figure 4.9 Installing Top Central Piece of Flow Deflector	48
Figure 4.10 Installing Lower Side Piece of Flow Deflector.....	49
Figure 4.11 Results of Near-Field Noise Measurements W / WO NAD for F-404 Engine	50
Figure 4.12 Results of Far-Field Noise Measurements at Solomons Island (2 miles distant) W/WO NAD for F-404 Engine	50
Figure 4.13 Near-Field Noise Reductions With NAD and F-404 Engine @ afterburner at a distance of 90 feet.....	54
Figure 4.14 Far-Field Noise Reductions With NAD and F-404 Engine @ afterburner and 2 miles	54

LIST OF ACRONYMS

AAE	Aerospace Auxiliary Equipment
AAR	Annular After Reactor
A/B	After-burning
AF	Air Force
AFB	Air Force Base
AICUZ	Air Installation Compatible Use Zones
CF6	Line of jet aircraft engines manufactured by General Electric
CFD	Computational Fluid Dynamics
CFR	Code of Federal Regulations
dB	decibel ($= 20 \log (P / P_{ref} $, where $P_{ref} = 20$ microPascals)
dBA	decibel, A scale (weighted according to sensitivity of human hearing)
dBL	decibel, L scale
DoD	Department of Defense
DoE	Department of Energy
ECAM	Environmental Cost Analysis Methodology
EPA	Environmental Protection Agency
EPR	Engine Pressure Ratio
ESTCP	Environmental Security Technology Certification Program
Far-Field	Area of sound field where: (a) noise source may be considered a point, and (b) significant absorption of sound by atmosphere may have occurred.
Free-Field	Area of sound field where (a) noise source may be considered a point, but (b) no significant sound absorption by the atmosphere has occurred.
FOD	Loose, small pieces of solid material in jet engine test area
FPNP (fpnp)	Frequency of peak noise production
Hz	Hertz
IRP	Military power, maximum jet engine power w/o after-burner
°F	Degrees Fahrenheit
GSE	Ground Support Equipment
JETC	Jet Engine Test Cells
JSF	Joint Strike Fighter
k	Thousand
lbs	pounds
LCC	Life Cycle Costs
Leq	Equivalent continuous sound level
LF	Low Frequency
LLeq	Equivalent continuous sound level, L scale values
M	Million
Mach Number	Dimensionless value of velocity / speed of sound (U/a)
MILCON	Military Construction
Military Power	See IRP, above

NAD	Noise Attenuation Device
NARF	Navy Aviation Rework Facility
NAVAIR	Department in the Navy Responsible for Naval Air Operations
NAWC PR	Naval Air Weapons Center, Patuxent River MD
Near-Field	Area near a sound source where sound source not considered a point
NAVFAC ESC	Naval Facilities Engineering Service Center
NON – NARF	Non- Navy Aviation Rework Facility
NSWC Dahlgren	Naval Surface Warfare Center, Dahlgren VA
OETF	Outdoor Engine Test Facility
OSHA	Occupational Safety and Health Administration
P	Pressure
PEWG	DoD’s Propulsion Environmental Working Group
Pi	Sound pressure over a sound 1/3 octave, i
Pref	Reference pressure for calculating sound levels in dB
PHOENICS	Commercially available CFD code
QA	Quality Assurance
QC	Quality Control
Rho	fluid density (mass / unit volume)
SERDP	Strategic Environmental Research and Development Program
Strouhal Number	Dimensionless number characterizing natural frequencies arising in a flow field as a function geometries and fluid properties
W/WO	With/Without

ACKNOWLEDGEMENTS

Funding for the design and testing of this full-scale Noise Attenuation Device (NAD) was provided by Navy Environmental Sustainability Development to Integration (NESDI) program. The engineering basis for the NAD was developed from sub-scale test results from the project “Reduction of Particulate Emissions From Jet Engine Test Cells (JETCs) Using an Annular After-Reactor (AAR)” that was co-sponsored by the Strategic Environmental Research and Development Program (SERDP) and NESDI. Those sub-scale data provided the basis for designing a full-scale NAD for application to the Navy’s F-414 jet engine operating at after-burner power.

Many individuals and several organizations contributed to the design and testing of the full-scale Noise Attenuation Device (NAD) demonstrated on this project. These included:

- Those providing support in the technical design and construction of the NAD from GE Energy and Environmental Research Corporation (GE-EER). These included Dr. Larry Swanson, Pete Maly, and Bob Elliot. Dr. Swanson provided the initial CFD modeling for the NAD, Pete Maly was shop foreman for its construction, and Bob Elliot did a masterful job of actually carrying out construction of the NAD at the GE-EER shop in Santa Ana CA. Bob provided many technical ideas on how to make the assembly and mechanical features of the NAD work together and was able to handle, manipulate, and assemble, in the shop, these 10-ton pieces. His help was indispensable.
- Dr. Marlund Hale reviewed the design features and NAD construction with the view, primarily, of eliminating harmonic resonances of the structure.
- Ms. Erin Morris of the NAVFAC ESC Design Group provided great support in putting the design ideas that we were working out onto drawings that permitted the NAD to be built. Her skill and patience was greatly appreciated.
- Dr. Howard Gaberson provided initial valuable consultation on noise measurements and on the use of recording instrumentation available at NAVFAC ESC.
- Dr. George Warren provided assistance in designing instrumentation for monitoring NAD vibrations in the field;
- Ian Stewart assembled a rather complex field instrumentation package (temperatures, pressures and vibration) for the J-52 engine tests at Naval Air Weapons Center, Patuxent River (NAWC PR).
- Many others were involved in the design, construction and testing of sub- and small-scale NAD test devices that preceded the design and construction of the full-scale NAD. Ray Capillino served as on-site co-ordinator for both the sub- and small-scale test systems. He had the enthusiastic support of Jeff McCallister and Douglas Petrie. Mike Hanks provided superb and essential assistance in the design and implementation of instrumentation schemes for both the sub- and small-scale systems. Ed Durlak assisted in

the design of the small-scale test system and with the execution of those tests, and provided a welcome technical perspective. Dr. Calvin Kodres provided important initial modeling results for both the sub- and small-scale test systems, and Tony Thomas of Thomas International provided many essential pieces of test hardware on short time scales to help keep the tests going.

- The test team at NAWC PR, led by Bill Cheeseman, was exceptional in helping to conduct both the J-52 and the F-404 engine tests. Ben Anderson ran the engines, Bobby Morgan kept things organized at the test pad, many others provided assistance in assembling the NAD, installing the engine, assisting with the engine runs, and recording noise data. Jennifer Paulk was always available to help, and also coordinated the far-field noise recording function. Micheal Kordich of Naval Surface Warfare Center, Dahlgren, provided analysis of noise data collected at both near and far-field sites. David Leunig (Lakehurst NAS) was the initial NAVAIR contact in attempting to put together full-scale NAD tests for the F-414 engine, and provided initial direction for the testing of the J-52 and F-404 engines.
- It is with great sadness that we note the passing of both Mike Hanks and Jeff McCallister due to separate accidental incidents following completion of the small-scale tests.

1.0 INTRODUCTION

1.1 Background

Noise can cause auditory (hearing loss, including deafness) and non-auditory health effects (e.g., hypertension, nervous disorders, etc.), interfere with speech, disturb sleep, affect the performance of children in school, cause changes in the behavior of wildlife, decrease real estate values, and affect historical and archaeological sites by induced structural vibrations. Although noise produced by military aircraft operations is not as highly regulated as other environmental issues, it is a major concern for activities engaged in air operations. Noise from the engines of jet aircraft is one of the most common sources of tension between the surrounding communities and DoD air bases, and the military is aggressively pursuing any and all means for reducing its impact. The reduction of noise produced by two of the Navy's high-performance tactical jet engines (the J-52 and F-404) during static testing is the subject of this report.

To reduce the noise "footprint" of the DoD's military operations large investments are being made to develop technologies to (a) reduce jet engine noise (sound pressures produced) by 2 to 3 dBA; (b) install extensive outdoor test facilities for monitoring, modeling, and learning more of the effects of aircraft noise; and (c) develop noise modeling tools. For the typical listener, a 3-decibel dBA change is barely perceptible; a 5 dBA change is quite noticeable; a 10 dBA change is perceived to be twice (or half) as loud and is quite dramatic to the listener.

[Note: The decibel (dB) is the unit of measurement commonly used to quantify sound pressures. It expresses the level of sound pressure relative to a reference pressure of 20 micro-Pascals, that is at the threshold of human hearing for a frequency of 1000 Hz (Hertz). The frequency is important because of the highly variable sensitivity of human hearing to it, and when this variability is accounted for using weighting factors sound pressures are reported as dBA. If this variability is not accounted for, i.e., where weighting factors have not been applied to the individual frequencies of the noise spectrum to account for the sensitivity of human hearing, sound pressures are reported as dBL. Thus Leq , the equivalent continuous sound level, is determined from the logarithmic expression $Leq = 20 \log (P/P_{ref})$. This overall quantification of noise level is the logarithmic sum of the individual elements (P_i 's) of the noise spectrum that is most often divided up into 1/3 octaves for analysis). If the spectrum elements (P_i 's) are A-weighted during this summation process Leq is reported as dBA; if they are not weighted, Leq is reported as dBL. For most of our concerns the dBA values (the noise that we hear) are of greatest interest. However, if the interaction of the noise pressure waves with structures is of primary interest, Leq reported as dBL, is of greater utility. Some of the results discussed below are reported as both dBA and dBL.]

Typical sound levels vary from 60 dBA for normal conversation to 70 dBA for a vacuum cleaner to 130 dBA or more for a jet engine at 100 feet. OSHA regulations require that engineering controls be used or that personal protective equipment be provided for a worker exposed to sound levels greater than 85 dBA for more than 8 hours. As military aircraft engines become more powerful and noisier, aircraft operations expand, and land areas adjacent to military operational bases become more fully developed, tensions between the military and local authorities increase. This project supports the Navy Environmental Quality Requirement 2.IV.02a, Aircraft Noise Control, by demonstrating and validating a technology to reduce jet

engine noise by up to 20 dBA during static engine testing. These noise reductions will provide the DoD with an important new, and relatively inexpensive, approach for bringing aircraft ground noise levels within acceptable limits of surrounding communities

1.2 Project Objectives

NAVFAC ESC undertook this project to (a) demonstrate the Noise Attenuation Device (NAD - see Figure 1.1) for significantly reducing (by 15 - 20 dBA) the noise produced by the DoD's high-performance jet engines during stationary testing and aircraft run-up, and (b) qualify the NAD for testing it with the Navy F-414 engine. Testing of the NAD with the Navy's J-52 and F-404 engines was undertaken as a required preliminary step to the demonstration/validation of the NAD with the Navy F-414 engine. Successful testing with the F-414 engine may lead to the further evaluation of the NAD for use with other DoD jet engines, as well (see Table 1.1). Factors that must be considered include larger, low-by-pass jet engines as well as non-after-burning, high-by-pass engines such as the CF6-80-C2 used in C-5 aircraft.

1.3 Regulatory Drivers

The Noise Control Act of 1972 (42 U.S.C. 4901 et seq.) preempts control of the airspace to the Federal government and seeks to protect Americans from noise that jeopardizes their health or welfare. However, the most restrictive controls of military-generated noise has often been imposed by neighboring communities as both informal and formal complaints in response to DoD activities. Therefore community interactions, along with the existing local and/or state rules, have been the dominant driving force in efforts to reduce noise from military sources. To assist in addressing these concerns the DoD initiated the Air Installation Compatible Use Zones (AICUZ) program which provided that each air installation was to submit an AICUZ plan to local governments for consideration in comprehensive planning efforts. If adopted by local authorities, this plan could provide the air installation with significant protection from encroachment and incompatible development in areas adjacent to the base. The AICUZ plans include evaluation of land areas in the immediate vicinity of the air installation that may obstruct use of the needed airspace and where the public may be exposed to health and safety hazards of aircraft operations. It contains a Compatible Use Zones matrix based on noise exposure zones, potential accident zones, and other land uses. Development of new noise reducing technologies such as the NAD will help the DoD in its preparation of AICUZ plans and in preventing noise intrusion from high-performance aircraft operations into neighboring communities. In addition, development of the NAD will help the DoD meet OSHA regulations requiring that engineering controls be used, or personal protective equipment be provided, for a worker exposed to sound levels greater than 85 dBA for more than 8 hours.

1.4 Stakeholder/End User Issues

Use of the NAD at DoD facilities depends upon (a) the noise reduction needed at any particular military base location and the function for which the NAD is needed (i.e., for engine test pad or aircraft power check pads); (b) the extent of noise reduction achievable by the NAD; and (c) the engines for which the NAD has been qualified for use.

Where judged useful, the NAD represents a low-cost alternative to JETC's and Hush-Houses and as a possible replacement for aging ones. In tests to date, the NAD has been shown to be

especially effective in reducing the low frequency jet engine noise that is the most difficult to control (LF noise carries long distances and affects structures).

The cost of fabricating an NAD is approximately \$250K compared to \$12 to \$15M for the construction of a new JETC. Therefore savings for the installation of just one NAD in the place of a JETC would be in excess of \$12.0M.

Table 1.1 DoD Aircraft/Engines Having Potential for Application of NAD

Aircraft	Engine	Wing Span (feet)	Length (feet)	Height (feet)	Thrust lbs
F-15 Eagle	F100-PM-100, 200 or 229	42.8	63.8	18.5	F-15C/D: 23,450
F15E Strike Eagle	F100-PM-220 or 229	42.8	63.8	18.5	25,000 - 29,000
F-16 Fighting Falcon	F-100-PM-200/220/229	32.7	49.4	16	F-16C/D: 27,000
F/A -18 Hornet A, B, C, D	or F110-GE-100/129				F404-GE-400: 16,000
F/A - 18 Super Hornet	F404-GE-400/402	37.5	56	15.4	F404-GE-402: 18,000
E, F	F414-GE-400	44.75	60.25	16	22,000
F-22A Raptor	F-119-PW-100	44.5	62.1	16.7	35,000
C-5 Galaxy	TF-39 (GE)	222.9	147.1	65.1	43,000
C-17 Globemaster III	F117-PW-100	169.8	174	55.1	40,440
F-35-A, B, C, (JSF)	F135 (P&W), F136 (GE/RR)	A/B: 35, C:43 137 / 79 Wings Fwd /	A/B: 50.5, C:50.8	17.3	28,000 (dry) 43,000 (A/B)
B-1B Lancer	F-101-GE-102	Aft	146	34	>30,000 (A/B)
B-2 Spirit	F-118-GE-100	172	69	17	17,300
B-52H Stratofortress	TF33-P-3/103 (PW)	185	159.3	40.7	17,000 MAX



Figure 1.1 NAD installation, Including Flow Deflector, with F-404 Engine.

2.0 TECHNOLOGY DESCRIPTION

2.1 Technology Development and Application

The full-scale NAD is a cylindrically-shaped, empty carbon-steel pipe, 50 feet in length, 6 to 14 feet in diameter, and weighing 25 tons. It incorporates fluid dynamic control elements to catch, slow, and deflect the jet engine exhaust plume. This slowing works to reduce the intensity of the otherwise persistent noise-generating turbulent eddies of the jet, reducing the noise produced.

To ensure adequate slowing of the exhaust plume, the outlet of the NAD is blocked – or partially blocked (see Figures 2.1 and 2.2) – so that the flow does not have a clear shot to proceed straight through the NAD without significant slowing. Rather, the cross-sectional flow area is more than doubled as most of the flow is forced through perforations in the side walls into an annular flow region, and then required to change directions twice before exiting the NAD. But changing flow direction requires pressure differentials and the required pressure head is obtained from that of the high-velocity jet exhaust. At the air inlet to a jet engine, for example, the air is slowed, and compressed by the inlet diffuser – a region of gradually increasing cross-sectional flow area. In the NAD, pressure is recovered by a similar “diffuser” effect. That head is then used to turn and maintain the flow through the perforated side-walls and turn it back again to the axial direction in the annular region of the NAD. In this way the NAD slows the flow, reducing the power of noise production, and serves as a shroud for the major noise-producing regions of the jet.

The use of the NAD for noise reduction became apparent during the co-execution of SERDP and Navy projects evaluating the annular after reactor (AAR) for the reduction of particulate matter and nitrogen oxide emissions from jet engines during static testing. The results of those tests showed that the AAR also significantly reduced noise during sub-scale jet engine testing and the full-scale AAR development effort was redirected to demonstrate its use as a NAD.

This project has now demonstrated the NAD for reducing noise during the static testing of the J-52 and F-404 full-scale jet engines. Jet noise is produced, predominantly, in two regions of the jet plume: the main jet, or core region, and in the mixing layer (see Figure 2.3). The frequency spectrum of the noise is a combination of the noise produced by these two sources, and the frequency of peak noise production (f_{np}), predicted by the Strouhal Number, decreases with engine diameter. For the two sub-scale jet engines tested prior to this project, the f_{np}'s were 5000 and 1800 Hz, compared to full-scale jet engines where the f_{np} is in the low hundreds of Hz.

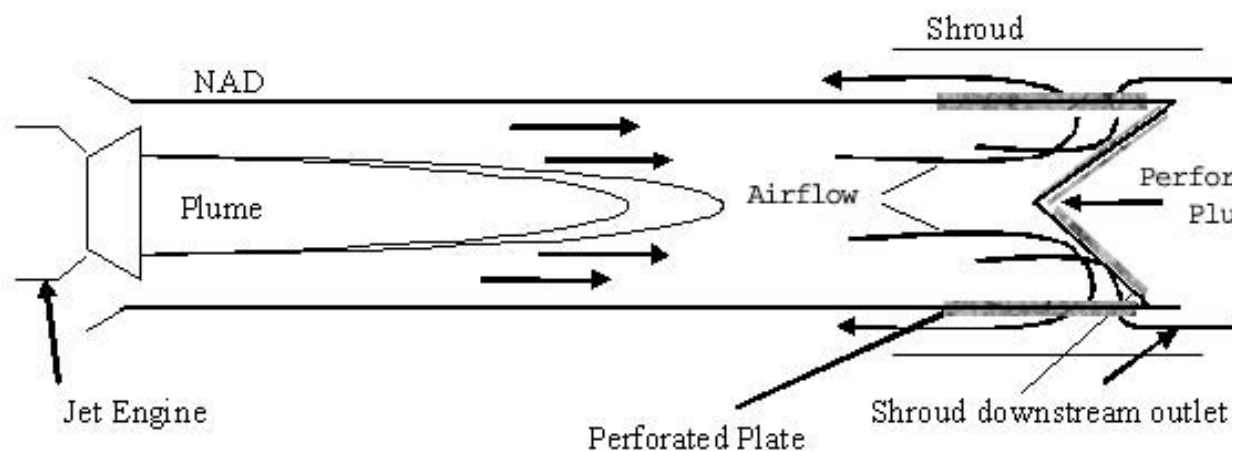
The intensity of the noise produced by the jet is (see Lighthill's formula, Reference 1):

$$\text{Jet Acoustic Power} = \text{const} (\rho) D^2 (U^3) (\text{Mach}^5)$$

and shows the high dependence of jet noise production on the velocity (U) of the jet. At the high velocities characteristic of military jet engine exhausts (2000 – 4500 ft / second) the conversion of kinetic flow energy to acoustic energy (noise) dramatically increases. Therefore, a way to reduce the intensity of the turbulence and the production of noise concurrently is to slow the jet plume as quickly as possible.

The NAD does this by catching the exhaust plume in an exhaust tunnel (see Figures 1.1, 2.1, and 2.2) and mixing the exhaust in a confined region with approximately three times (by mass) air as the quantity of engine exhaust flow. Adding the air mass to the exhaust flow reduces the average velocity of the resulting mixed stream by a factor of about four (conservation of momentum). By reducing the velocity the intensity of the turbulent fluctuations is reduced, and according to Lighthill's formula, the acoustic power emitted by the jet is also dramatically reduced.

Figure 2.4 shows the computational domain for modeling the flow field through the NAD to compliment the schematic flow paths through the NAD (Figure 2.3). The technical objectives of the modeling were to ensure a safe, acceptable flow of the jet exhaust plume through the NAD to reach the target noise reductions. Of course, by adding three times the mass of cold air (at 70°F) to that of the hot jet exhaust (sometimes reaching 3800°F) the hot exhaust is also cooled as the streams become intimately mixed. The length and diameter of the NAD were sized to accommodate this mixing process so that by the time the core of the hot exhaust plume reached the outlet end of the NAD its temperature was reduced to less than 1200°F, the design limit set to protect NAD structural elements from over-heating during the short periods of engine operation at after-burner power.



- GOALS**
- (a) slow jet exhaust by mixing with entrained air (momentum exchange)
 - (b) cool exhaust (3800°F) with 3:1 ratio of entrained air (thermal mixing)
 - (c) convert velocity head to pressure head for changing flow direction

Figure 2.1 Directional Flows in NAD.



(a) NAD Full Blockage Cone (NAD c)



(b) Partial Clockage Cone (NAD d)

Figure 2.2 (a) Full Blockage for J-52 Engine Testing, and (b) Partial blockage for F-404.

NAD REDUCES NOISE BY REDUCING VELOCITY OF JET EXHAUST

$$\text{Jet Acoustic Power} \sim 2 \pi U^8 D^2 / a_0^5 \quad (\text{LIGHTHILL'S FORMULA})$$

FREQUENCY SPECTRUM OF NOISE

S = Strouhal No. = Dimensionless Frequency

$$= \frac{nD}{V} = f(Re) \quad (\text{Schlichting})$$

$S \sim 0.30$ (sub-sonic jets)

n = frequency of peak power $\sim \frac{SV}{D} = 5000$ (for sub-scale jet)

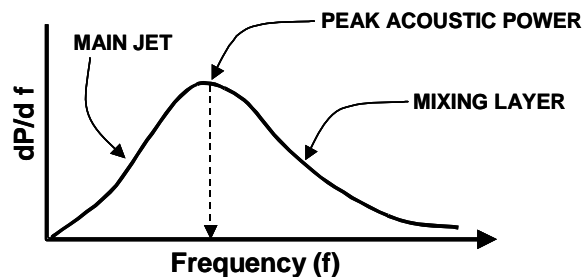


Figure 2.3 Strouhal Number and Determination of FPNP.

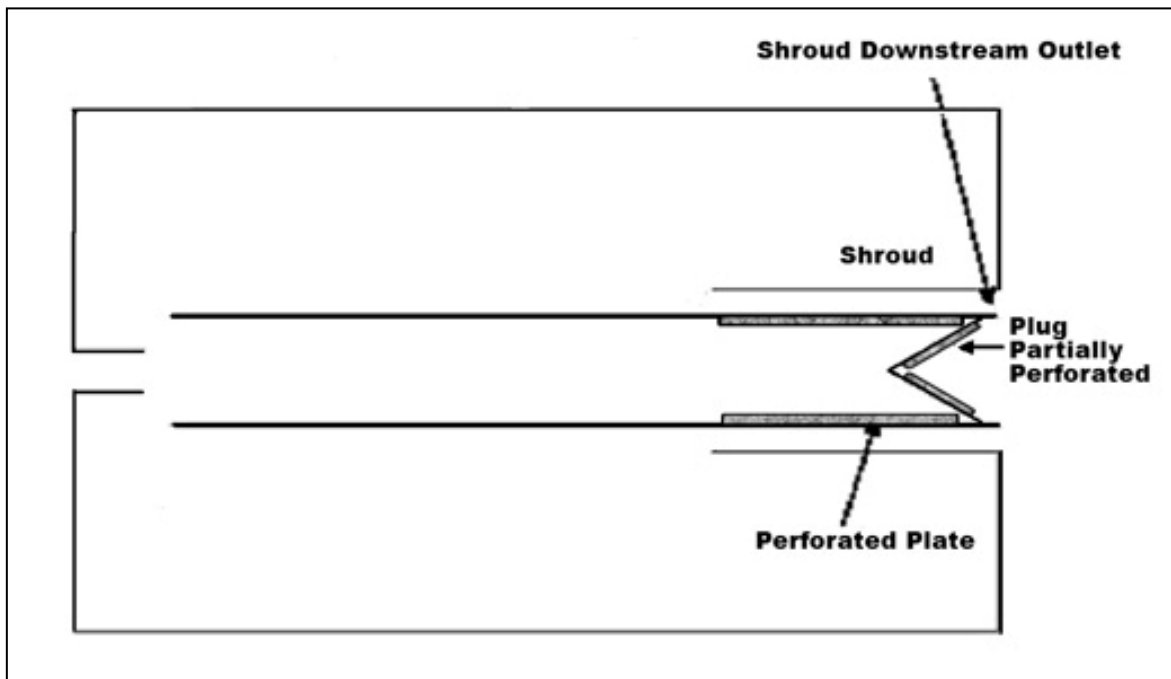


Figure 2.4 CFD Modeling Domain Without Flow Deflector.

Because the current version of the NAD was designed to be used with the F-414 engine, it is also adequate for testing lower powered engines, e.g., the J-52 and F-404, that have lower mass flows and thermal loadings. The larger F-100 engine, used in the Air Forces F-15 and F-16 aircraft, has not yet been evaluated for use with the NAD, nor have the F-119 and F-135 engines (F-22 and JSF aircraft, respectively). Because these latter engines present significantly greater thermal loadings than the F-414, it is expected that additional CFD modeling will be required, leading to a larger, modified NAD. Similar CFD modeling will be required for assessing the applicability of the NAD to large, non-after-burning engines such as the CF6-80-C2 (CF6) engine designated for the upgraded C-5 transport.

The application of the NAD to the CF6 engine is interesting, and may be an easier technical fit for the NAD than are the after-burning (A/B) engines. The CF6, physically, is a much larger engine (8.5 foot inlet diameter, cf., 3 foot diameter for tactical engines), and its high engine by-pass ratio (total air flow / central engine exhaust flow) produces a much cooler and slower-moving exhaust stream. The higher fluid density and large engine diameter favor greater noise production, but the lower velocities favor less noise production. Because of the larger jet exhaust diameter the noise produced will be concentrated in frequencies lower than those for the high-performance engines.

The CF6 engine line incorporates many engine models and upgrades to produce thrusts ranging from 40,000 to 70,000 pounds. It has been in service since the 1960s' when the first version of it was first delivered as the TF39 engine to the Air Force as the original engine for the C-5 aircraft. As a result, the CF6 now powers more transport aircraft than any other jet engine produced and represents the first application of the high by-pass design technology that has dramatically improved transport jet engine performance since the TF39 was introduced. Because of the exhaust conditions produced by the CF6 there is no question as to whether the NAD can be used

with it. Rather it will become an economic question as to the size and cost of producing a NAD appropriate for a CF6 engine, and the promise of noise attenuation that will be possible. These issues will be examined further as development of the NAD continues.

2.2 Sub- and Small-Scale Development of NAD Technology

During the initial sub- and small-scale AAR testing (i.e., one for a 1.4-inch diameter simulated jet engine and the second for a 4-inch diameter turbo-jet drone engine, see Figures 2.5 and 2.6), noise reductions of 15 to 20 dBA were observed. The noise reductions occurred across a broad range of frequencies centered about the frequency of peak noise production (f_{pn}). The upper curve in Figure 2.7a shows a peak in noise production at a frequency of 5000 Hz. Noise attenuation by the AAR is shown by the position of the lowest curve, and attenuation extends from a low of 50 to greater than 8000 Hz. Figure 2.7b shows net noise reduction (insertion loss) for the small-scale tests (4.0-inch diameter engine). Here the frequency of peak noise production (f_{pn}) has shifted to about 1800 Hz and noise attenuation extends from about 50 to 16,000 Hz. The shift in the f_{pn} (see Figure 2.3) is in accordance with the Strouhal number (S), where $f = SV/D$, f is the frequency, $S = 0.20$ for sub-sonic jets (Reference 2), and V and D are the velocity and the diameter of the jet, respectively. If V is held constant, as was approximately so for the two sub-scale tests simulating military power conditions, f_{pn} becomes proportional to $1.0 / D$. That is, f_{pn} shifts to lower frequencies to the same extent and in the same direction as the noise frequencies characteristic of the larger diameter AAR. Therefore to the extent that the AAR attenuates noise for one engine size, it would be expected to similarly attenuate noise for an engine of another size when the AAR is scaled according to engine diameter.



Figure 2.5 Sub-Scale 1-1/2 inch Simulated Engine and AAR for Noise Testing.

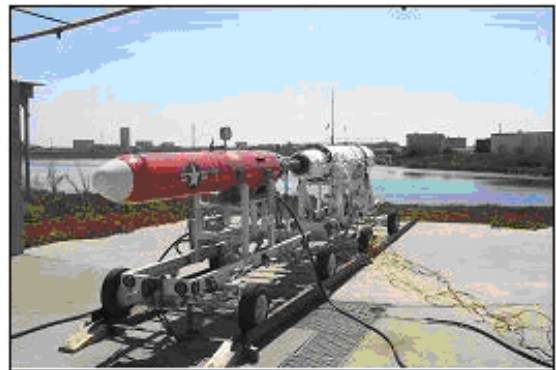
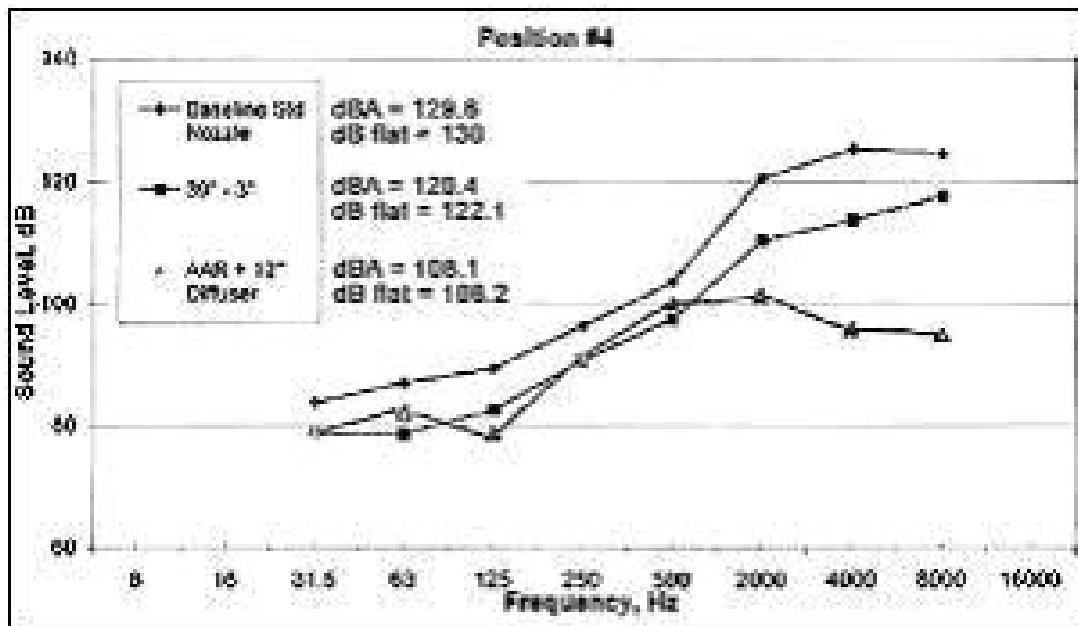
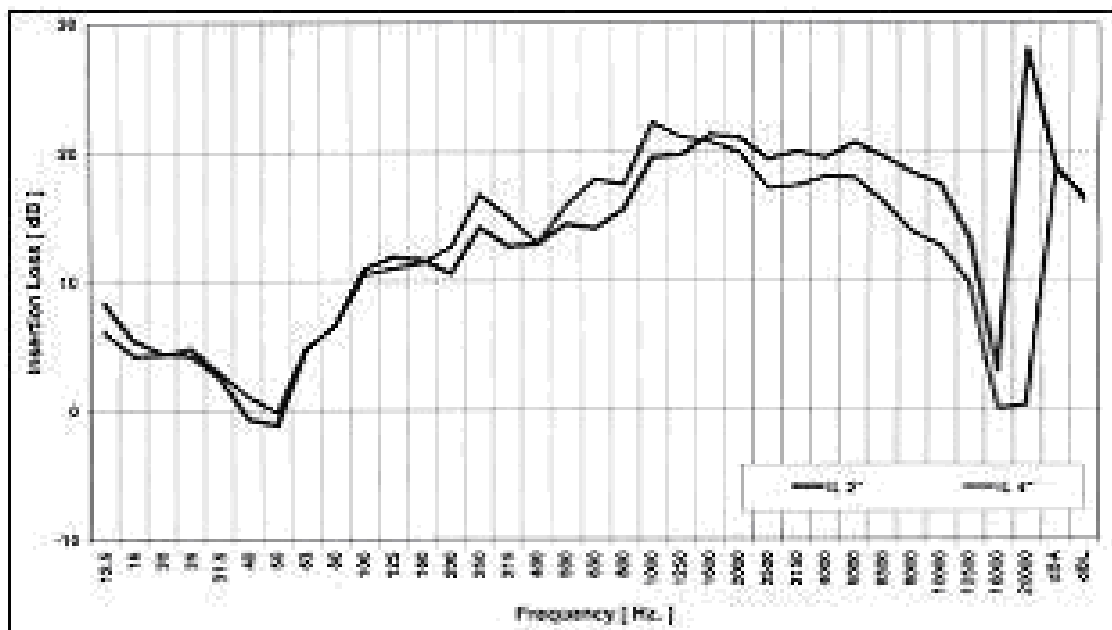


Figure 2.6 4-inch Diameter Target Drone Engine with AAR for Noise Testing.



(a) With 1-1/2 inch Sub-Scale Engine.



(b) With 4-inch Drone Engine.

Figure 2.7 Noise Measurement Results.

2.3 Advantages and Limitations of the NAD Technology

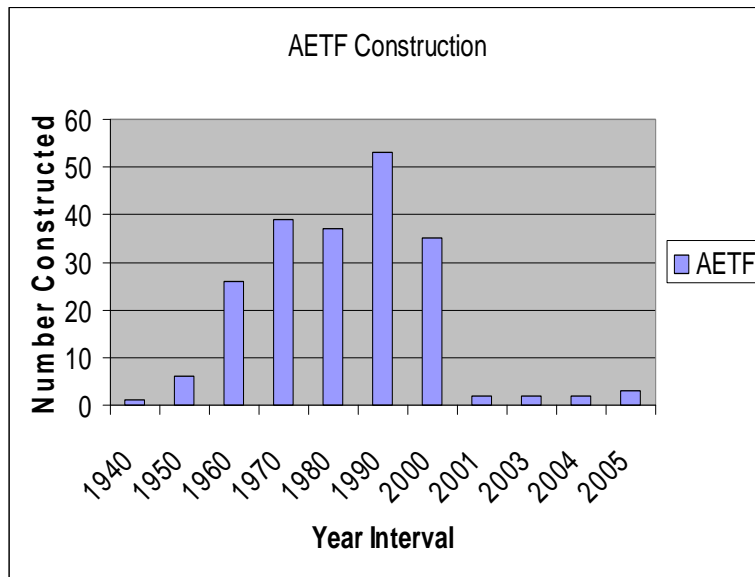
The advantage of the NAD is to reduce noise from statically tested engines and stationary aircraft by 20 dBA for a small investment. Millions of dollars are being spent in attempts to reduce aircraft noise by marginal amounts (e.g., 2 or 3 dBA for the JSF aircraft). The NAD can also be used for engine test purposes for which enclosed JETCs (Jet Engine Test Cells) are not applicable because of excess costs. Being transportable, the NAD can also be placed at different locations at an activity to facilitate the run-up of engines at aircraft high power test pads.

In a recent visit to Tinker AFB the question was raised if the NAD could be mounted on wheels so that it could be moved and used for run-up of aircraft out on the parking apron following maintenance. A tour of the parking apron at Tinker seemed to indicate that, if workable, such a process could not only reduce noise levels but reduce the considerable costs in having to move these large aircraft from one location to another on the base in order to make needed ground engine tests. Evaluation of other DoD locations is proceeding, but in discussions with the AF AICUZ program manager at Brooks AFB it seems clear that there is no one answer that is going to be applied to all bases. Each base has its own noise reduction concerns. The responsibility for addressing them is a local one although funding needed for implementing corrections must normally come from major commands.

Table 2.1 shows the types of aircraft / engine acoustical facilities in use by the Navy and Figure 2.8 shows the history of when those facilities were built. Considering their estimated 15-year life, it is clear that many will soon need to be replaced or renovated, becoming a major reconstruction problem for the Navy. Further, the reduction of noise at air installations is an unresolved problem expanding in importance for the DoD. As the cost of fabricating an NAD is approximately \$250k compared to the cost of \$12 to \$15M for the construction of a new JETC, the NAD may be able to help address this increasingly important DOD problem in a cost-effective manner.

Table 2.1 Inventory of Navy Aircraft / Engine Acoustical Facilities

Cat Code	Facility Class	Inventory
211-01	Aircraft Acoustical Enclosure (NON-NARF)	13
211-81	Engine Test Cell (NON-NARF)	55
211-83	Engine Test Cell (NARF)	9
211-88	Power Check Pad With Sound Suppression (NON-NARF)	19
211-89	Power Check Pad Without Sound Suppression (NON-NARF)	102
211-94	Aircraft Power Check Facilities (NARF)	5
	Total	203



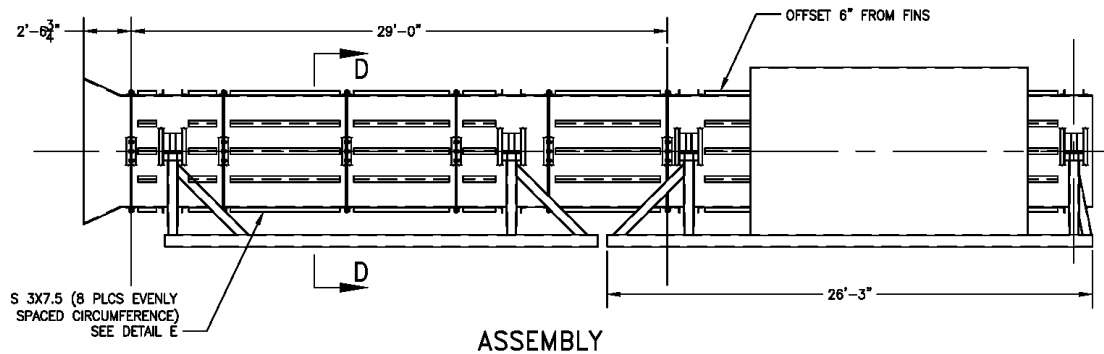
- Expected Service Life
- Component Life
 - Augmenter: 15 years
 - Reflective Floor Coating: 8 Years
- Engine Service Life

Figure 2.8 Construction History of Navy Aircraft/Engine Acoustical Facilities.

3.0 DESIGN OF DEMONSTRATION FIELD TEST

3.1 Demonstration Test Objectives

Based on the sub- and small-scale noise reduction test results and the Navy's need for noise reduction during static engine testing, it was decided to proceed with design of an NAD (an AAR of simplified design for noise reduction) that could be demonstrated on a full-scale jet engine. Discussions with NAVAIR personnel had indicated that the engine of greatest interest to them for demonstrating a prototype NAD was the F-414 engine. Therefore the design objectives for the full-scale NAD (see Figure 3.1) were to demonstrate: (a) noise reductions of 15 to 20 dBA; (b) thermal and fluid dynamic compliance with after-burner operating conditions of the F-414 engine (3,900°F); (c) robustness and reliability in an intense vibrational and structurally demanding environment; (d) transportability; (e) simplicity of design and low operating cost – no pumps, compressor or water injection; and (f) low capital cost. These design criteria were used to design and build the NAD and remained unchanged except for the fact that test results for the J-52 engine gave promise that noise reductions for engines having an after-burner (e.g., F-404 and F-414 engines) could reach or exceed 20 dBA.



DESIGN OBJECTIVES

- (a) Reduce Engine Noise by 15 – 20 dBA
- (b) Applicable to F-414 Engine @ A/B
- (c) Robust and Reliable in Structurally Demanding Environment
- (d) Transportable
- (e) Simplicity of Design / Low Operating Cost
- (f) Low Capital Cost

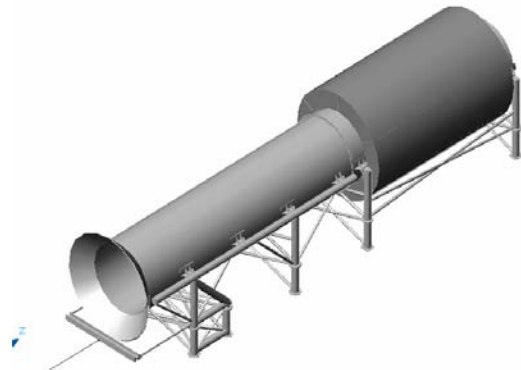


Figure 3.1 Schematic and Design Objectives of Full-Scale NAD, Constructed on Two Skids, for Noise Attenuation of the F-414 Engine.

3.2 CFD Modeling and Design Basis for Full-Scale NAD

The extremely large scale-up from a sub-scale 4-inch diameter target drone engine being tested on a sub-scale AAR (NAD) operating at military power to an F-414 engine operating at after-burner power presented significant technical difficulties. However, CFD modeling of the fluid flows through the NAD helped to both identify and solve many potential problem areas. Other practical concerns were that the NAD would have to be constructed to withstand the extreme stresses presented by field-testing aft of the jet engine, and that it would also have to meet the operational and safety requirements of aircraft engine test personnel.

Consideration of the F-414 engines geometrical test configuration (how mounted, height above ground level, nozzle size, etc.) and the maximum and minimum power levels at which it would operate (engine exhaust mass flows, temperatures, and velocities) provided the fundamental data for scaling up and designing the NAD. Geometrical considerations for the F-414 engine indicated that the centerline of the NAD needed to be about 5 feet above ground level (It later turned out that this was a good dimension to use for the J-52 and F-404 engines, as well.) Other than that, the cross-sectional area, length, and other dimensions and specifications of the NAD were determined from requirements for it being able to satisfactorily handle the exhaust flows from the engine at maximum after-burner conditions (temperatures of the order of 3900°F, while the maximum service temperature of mild steel is about 1200°F – a higher grade of steel could

easily have doubled or tripled the cost of fabricating the NAD). Further it was desired to make the NAD as simple and inexpensive device as possible so that the addition of any auxiliary system (e.g., water cooling) which could break down during testing and which, itself, could cost as much as the NAD, was to be avoided. The NAD was to be a no-frills, low-cost device for reducing jet noise. Making it low-cost meant using air-cooling, and computational fluid dynamic (CFD) modeling was extensively used to arrive at a NAD design for which air-cooling was effective.

Those fluid dynamic principles and the requirement that the NAD needed to withstand an extremely hot, intense vibrational environment became the focus of much of the design effort for the NAD. Professor Waitz, a consultant on the SERDP project, had previously warned of his experience in observing a jet engine test, similar to what we would be conducting with the NAD, where the 1-inch thick steel walls were torn asunder during a jet engine test by the strong harmonic vibrations that had been set into motion by the jet exhaust passing through the exhaust tube (Reference 5). With that in mind, extreme care was taken to identify and address any part of the NAD structure that indicated that it could cause a structural resonance problem, and steps were taken to address this issue: (a) longitudinal segments of the main body of the NAD were broken into uneven lengths to reduce (eliminate) the potential for full- or partial-length longitudinal resonant body frequencies, and (b) numerous longitudinal and circumferential reinforcing bracing bars were added to the structure to reduce (eliminate) resonant frequencies that might tend to occur in isolated regions of the structure.

The initial CFD modeling was provided by GE-EER. Figure 3.2 indicates the initial parameters of this study, and Figure 3.3 shows an initial result that indicates how long the NAD must be to prevent overheating of the NAD at F-414 after-burning engine conditions. Figures 3.4 and 3.5 shows the calculated flow field results for velocity, Mach Number, pressure, and temperature that were used as the basis of the initial design of the NAD.

The NAD design was later formalized as the schematic layout shown in Figure 3.1. Some further design details are indicated on Figures 3.6 and 3.7.

The NAD was constructed of carbon steel with an upper service temperature of approximately 1200°F while the NAD would eventually be subjected to an operating environment of the F-414 engine at after burner conditions of 3900°F. The NAD would not be exposed to these extreme conditions for long periods of time, but exposure times of even a few minutes at after-burner was a hurdle that needed to be overcome to avoid rapid degradation (destruction) of the carbon steel structure. To address this, sufficient air needed to be entrained into the NAD along with the engine exhaust plume to provide an exhaust gas/air mixture which, when fully mixed, would have an average temperature that would not exceed 1200°F. This required that the NAD be of sufficient diameter to permit the entrainment of approximately a 3:1 ratio of air to exhaust gas, and that the NAD be of sufficient length to permit adequate mixing of the two (hot and cold) streams before the hot exhaust could impact upon the carbon steel containment walls or the end-piece of the NAD. Prior to their mixing, the entrained air layer would serve to insulate the walls from the high-temperature exhaust plume.

Sufficient exit area of the NAD was required to permit the flow of the mixed gas stream out through the perforated exit section of the NAD without generating excessive back-pressure. The exit section of the NAD also served as a diffuser section for recovery of pressure from the exhaust plume; the perforated walls mimicking the diverging walls of an ordinary diffuser so that fluid wall separation (which can limit diffuser pressure recovery) would not be a problem. The recovered pressure was then used to drive the mixed stream sideways, out through the NAD perforated walls, and then re-accelerated in both forward and backward directions in the outer annular passage to exit the NAD. This flow behavior is illustrated in Figure 2.1 and also Figures 3.4 and 3.5, which show CFD solutions of flows through the NAD for temperatures, pressures, and velocities. To arrive at these solutions proper NAD characteristics and dimensions had to be selected, as described above. Under-sizing the exit areas of the NAD could cause excessive back-pressures, limiting the quantity of air that could be entrained into the NAD and posing a threat of overheating it. Therefore it was necessary to determine both temperature and pressure profiles through the NAD to avoid any under-ventilated conditions and ensure proper flows through the NAD at after-burner conditions.

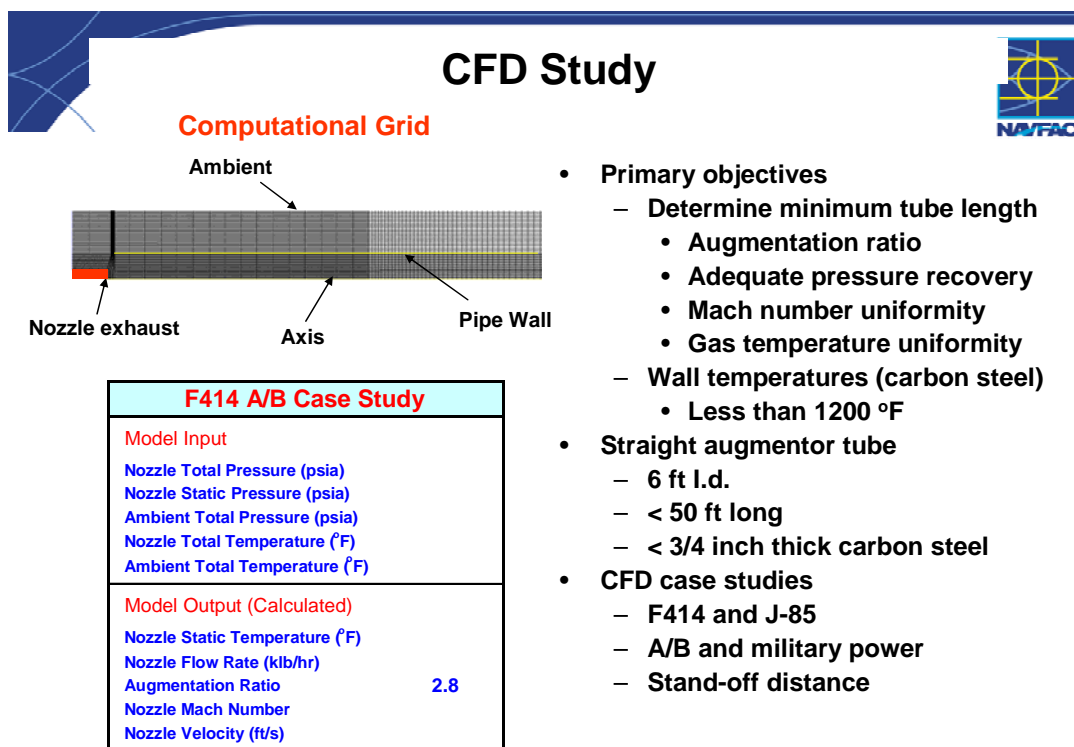
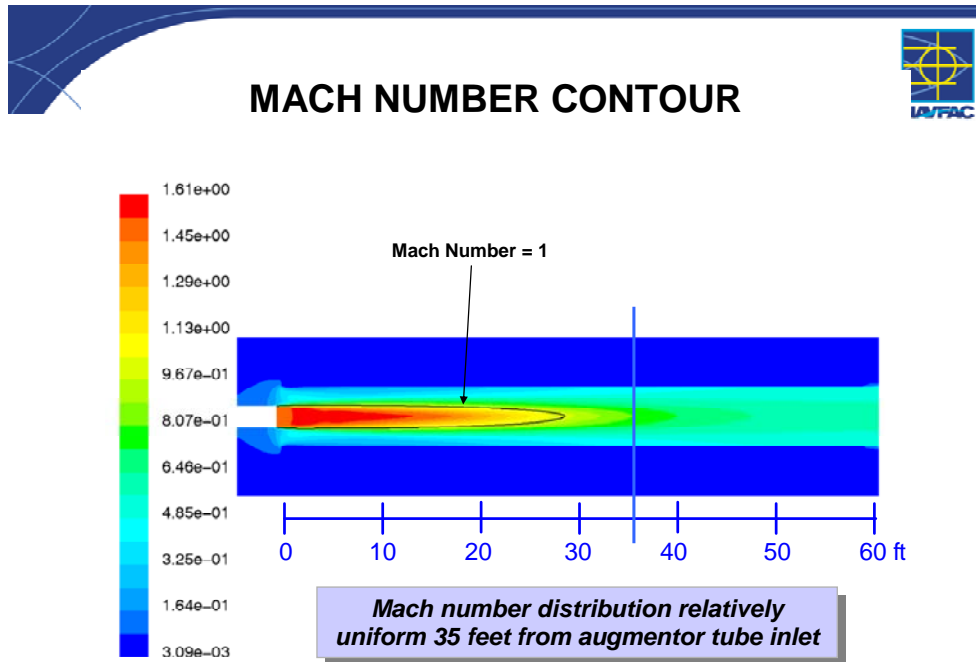


Figure 3.2 Parameters Used in Initial Conceptual CFD Study for NAD.



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Figure 3.3 Initial CFD Results Illustrating Minimum Needed Length for NAD.

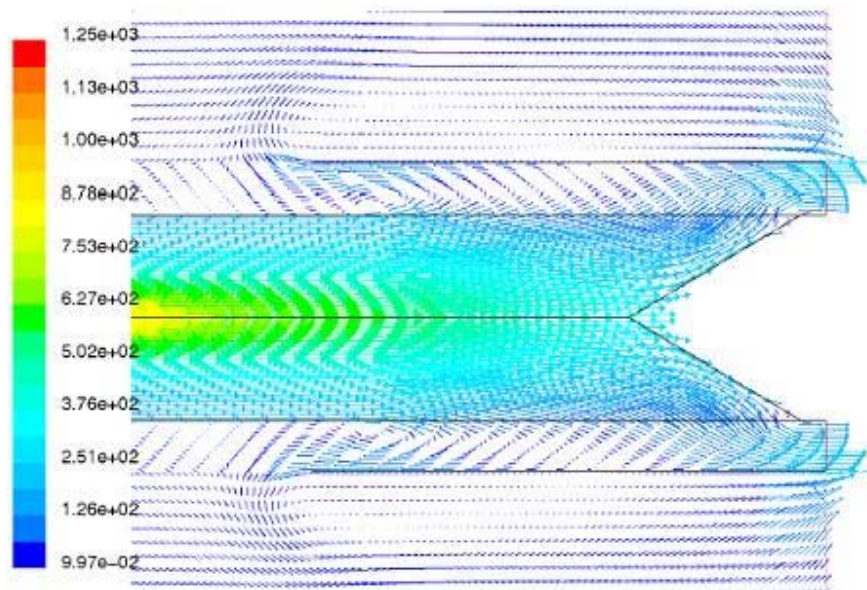
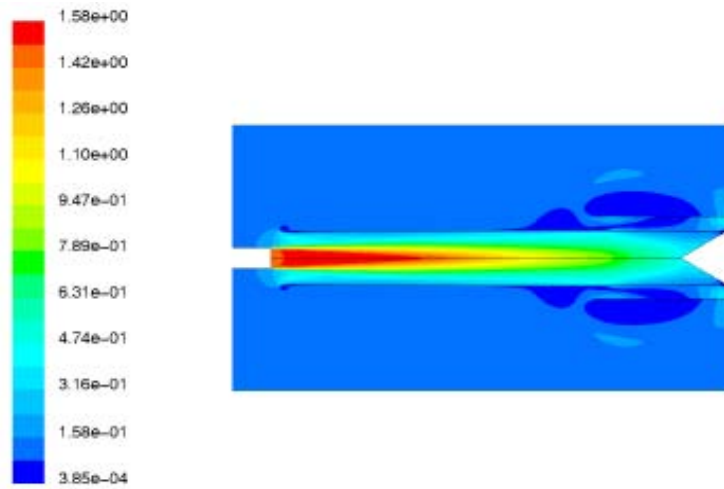
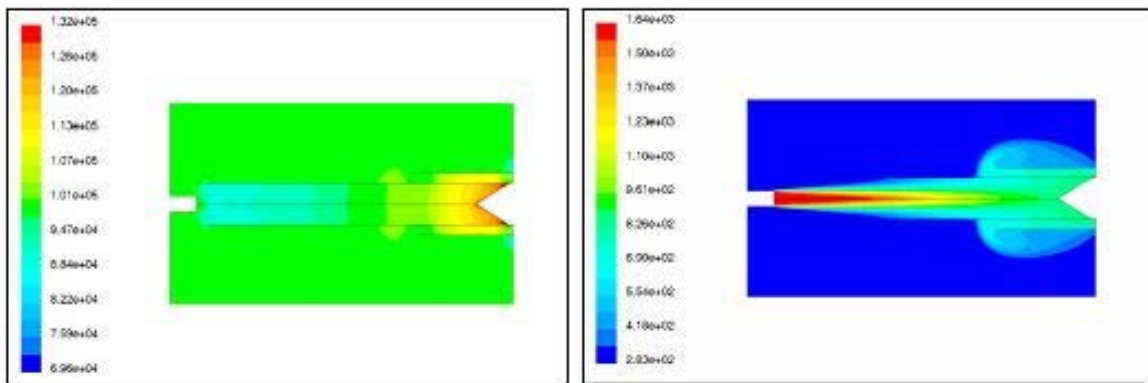


Figure 3.4 Calculated NAD Velocity Flow Field Results for F-414 Engine at After-Burner Without Flow Deflector.



(a) Mach Numbers



(b) Pressures

(c) Temperatures

Figure 3.5 Calculated NAD Mach Number, Pressure, and Temperature Results for F-414 Engine at After-Burner Without Flow Deflector.

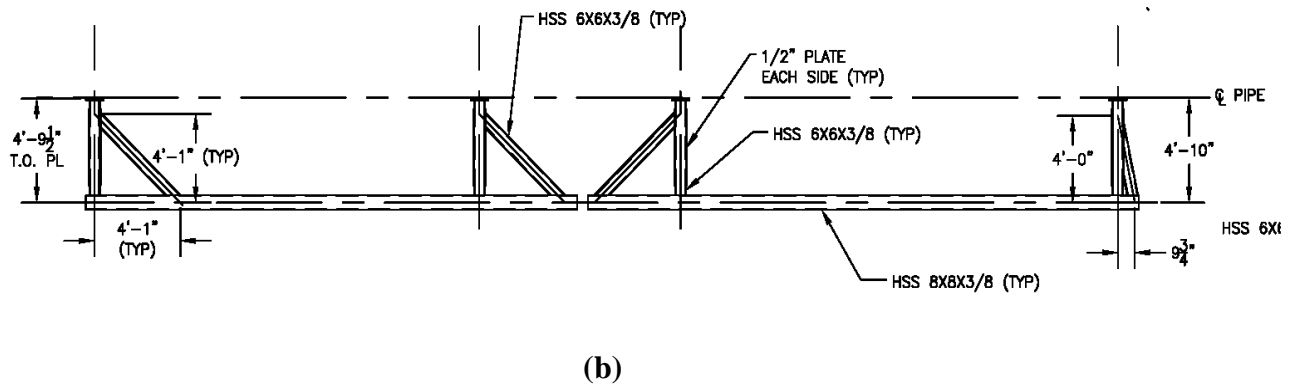
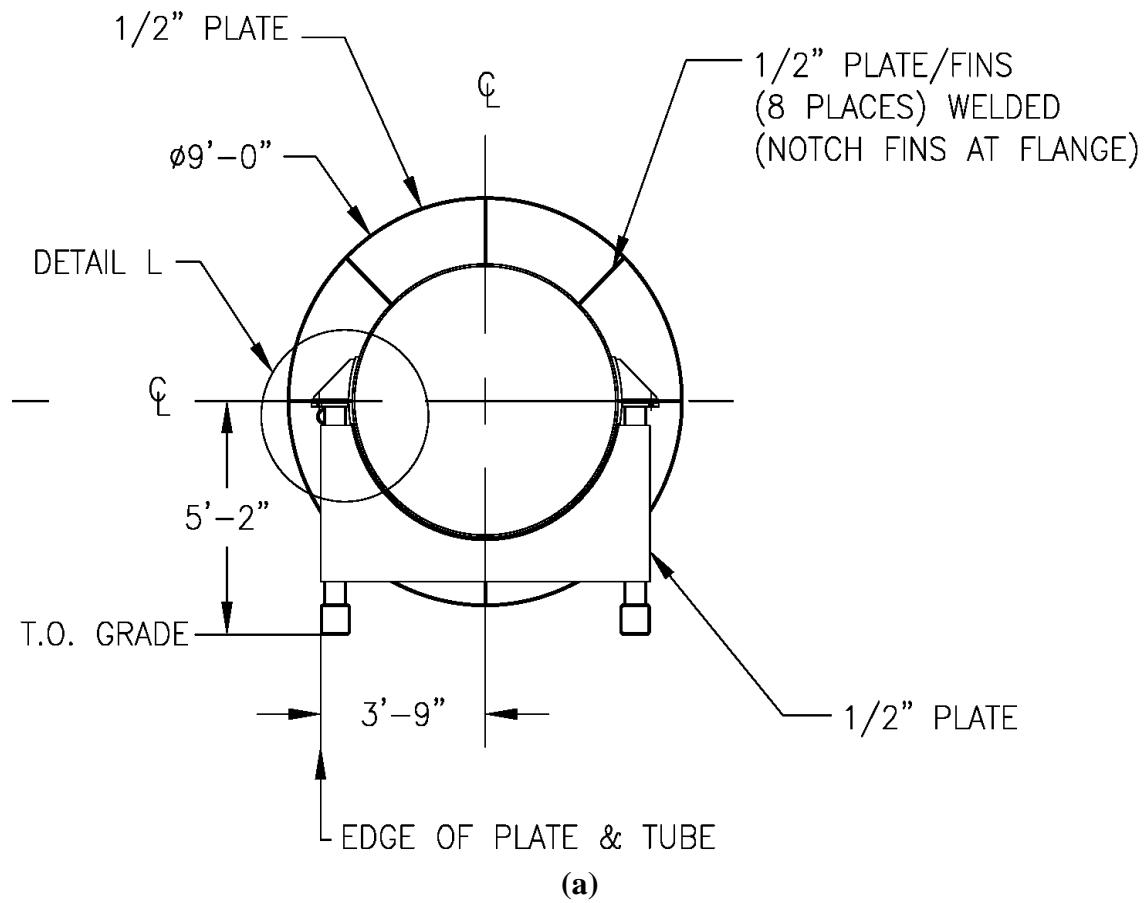


Figure 3.6 (a) Longitudinal Section, and (b) Detail of Support Structure of NAD.

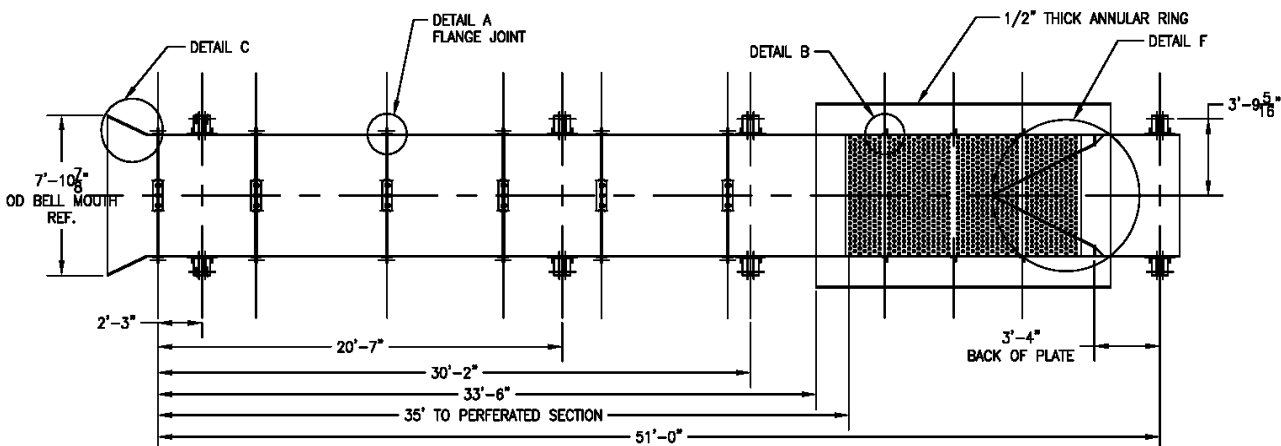


Figure 3.7 Internal Features of NAD.

3.3 NAD Fabrication

Figure 3.8 shows a photograph of the NAD during its fabrication for the J-52 test, and Figures 3.9 and 3.10 show the NAD during trial assembly of the NAD exhaust deflector pieces that were installed for testing of the F-404 engine.

3.4 Test Planning

3.4.1 Selecting Test Sites/Facilities

The test site selected for demonstration testing of the NAD was the Outdoor Engine Test Facility (OETF) at the NAWC PR. This test site was appropriate because: (a) all development and qualification testing of Navy aircraft engine test systems (e.g., engine control systems and engine handling systems) is conducted at this site before that equipment can be certified for use at other Navy locations; (b) this site is dedicated to the evaluation and qualification of candidate technologies for use as ground support equipment (GSE) for the Navy and there exists a ready availability of both qualified personnel and technical resources for assisting with carrying out the desired tests; (c) the site provides an environment in which the noise attenuating capabilities of the NAD can be measured and evaluated in both the near- and far-fields; (d) Navy personnel involved in the final approval and qualification of the NAD for use throughout the Navy are located at the nearby Lakehurst (NJ) Naval Air Station and work closely with personnel at the NAWC PR in evaluating and qualifying aircraft GSE such as the NAD; (e) the Navy's F-414 (and other) engines can be made available for testing the NAD at that location. Tests of the J-52 and F-404 engines that are reported here were scheduled as preliminary steps leading to the expected future testing of the F-414 engine. The OETF at the NAWC PR was, and is, the most desirable Navy test site for evaluation of the NAD with these engines.



Figure 3.8 NAD During Fabrication at GE-EER Plant in Santa Ana, California.



Figure 3.9 Exhaust Deflector Being Trial Assembled With NAD at GE-EER Site.



Figure 3.10 Rear View of NAD Assembled With Exhaust Deflector at GE-EER Test Facility.

The NAWC PR is the central command center for NAVAIR and for NAVAIR technological development. As noted above, qualification testing of much ground support equipment (GSE), such as the NAD, is conducted at NAWC PR. An overview of the OETF at Naval Air Weapons Center, Patuxent River is shown on Figure 3.11. On this view the test engines were located at the top of the left hand concrete strip. In the foreground is a large berm, about 15 feet in height at its peak, but tapering to test pad level on the right. It circles around to the left, forming a mild noise barrier on the right and bottom sides of the photo (the berm was installed at one time in an attempt to keep the noise of engine testing from base neighbors, but was unsuccessful). Figure 3.12 shows the test site as it is approached from the office area, and Figure 3.13 shows an overview of the entire test area, including the location of candidate far-field noise monitoring sites (Solomons Island was the far-field site of primary concern). Figures 1.1 and 3.14 show engine placement and other details of the test site.



Figure 3.11 Overhead View of OETF at NAWC PR with Engine and NAD Positions Indicated.



Figure 3.12 Ground-level view of OETF at NAWC PR.

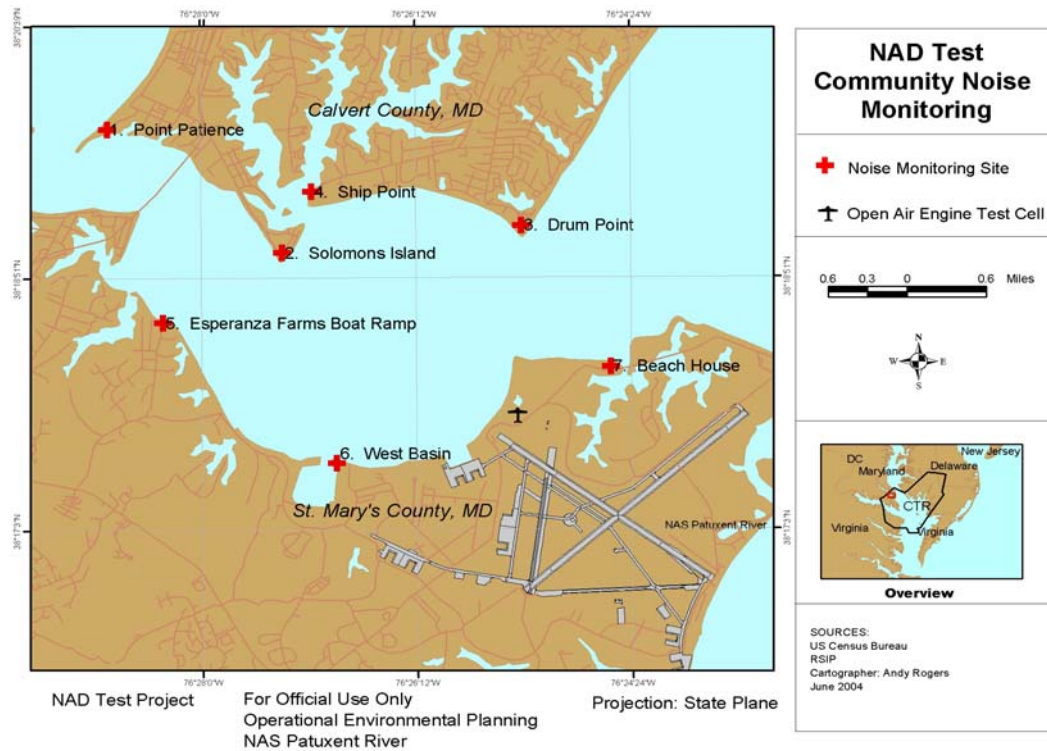


Figure 3.13 Area Surrounding NAWC PR Showing OETF and Far-Field Noise Measurement Locations.



Figure 3.14 NAD Installed for Testing with J-52 Engine – No Flow Deflector.

3.4.2 NAD Installation

The NAD was fabricated in California and transported across the country for testing at the Naval Air Weapons Center (NAWC PR). As modifications were made to the NAD between testing of the J-52 and F-404 engines, that trip across country was made both prior to and intermediate to the two tests. NAD transport was by two semi-truck trailers of the several NAD sections (two large main sections plus three smaller auxiliary pieces for the F-404 tests) to their storage site at Patuxent River, about 100 yards from the OETF test pad. The NAD was installed at the OETF after the test engine was already in place and preliminary engine check-out tests had been completed.

To install the NAD on the engine test pad a portable crane was used to first lift into place each of the two main components of the NAD (each about 25 feet in length, 8 feet in diameter, and weighing 20,000 lbs.) onto a semi-trailer truck bed. Each section was then transported to the test pad where it was again off-loaded and placed according to pre-marked locations on the test pad (see Figures 3.15, 3.16, and 3.17), determined in accordance with the test position of the engine to be tested. Once those two sections were in place, they were bolted together using sixty-four 1-inch bolts. High temperature packing was installed between the connecting flanges of the two connecting halves. This was all a very tedious job, and the installation including NAD placement, proper leveling and alignment of the two connecting main sections, alignment of the bolt holes, and installation of the packing between flanges took almost a week for the J-52 engine.

Installation of the NAD for the J-52 engine was complicated by the fact that the large portable crane was out of service and the smaller crane that was available had to be moved several times for each lift to obtain adequate lift leverage. However, we learned a lot about the installation process during the J-52 test to help when re-installation of the NAD for the F-404 engine was undertaken. The F-404 engine set-up was more complicated because of the addition of three additional exhaust deflector pieces, but as the large crane was available the installation took only slightly more than a day. Once the two large sections had been bolted together, they were each anchored to the concrete test pad with eight chains attached to each of the eight NAD support legs. The anchor chains were attached to tie-downs previously placed in the concrete. Their purpose was to minimize NAD movement and vibration during engine testing. Once the two main sections of the NAD were in place for the F-404 test, the three auxiliary pieces to the NAD (comprising the exhaust flow deflector), each weighing about 4000 lbs., were installed on the NAD and bolted into place.

Photographs of several aspects of the installation process are shown in Figures 3.15 through 3.29.



Figure 3.15 Crane Lifting Forward Section of NAD into Place.



Figure 3.16 Crane Lifting Aft Section of NAD into Place.



Figure 3.17 View Showing Bolted Sections of NAD, Reinforcing Elements, Thrust Turnbuckle, and Tie-Down Chains.



Figure 3.18 Moving Exhaust Cone (NADc) into Place for Attaching to NADc.



Figure 3.19 NADc “Cone” End-Piece Being Inserted into NAD for Attachment.



Figure 3.20 Alternative NADa “Grill” End-Piece Attached to NADa.



Figure 3.21 Internal View of Attached “Grill” (NADa) End-Piece.

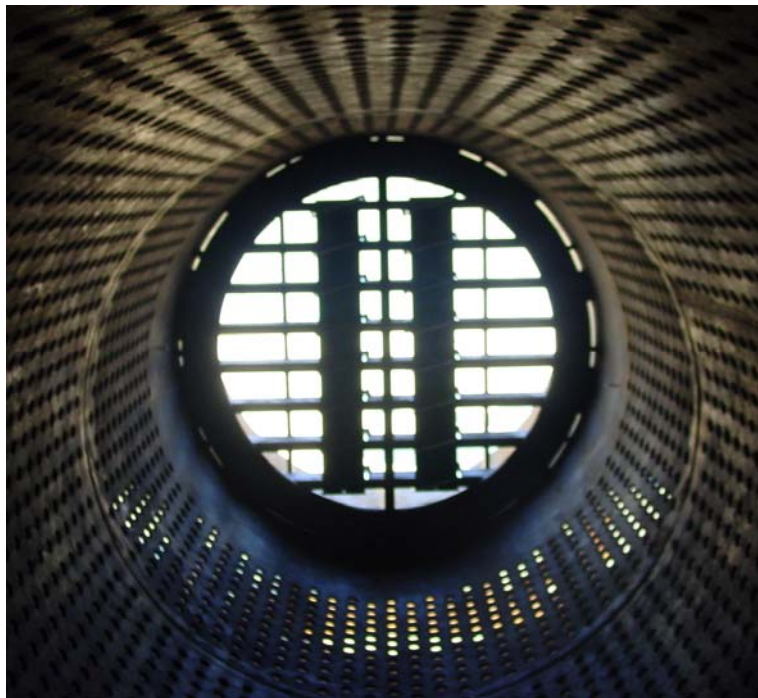


Figure 3.22 Internal View of “Grill With Plates” (NADb) End-Piece.



Figure 3.23 A Job Well-Done. After Allowing NAD to Cool From Previous Engine Run, “Plates” Were Installed in $\frac{3}{4}$ Hour Saving Critical Engine Test Time.



Figure 3.24 Installed Temperature, Pressure, and Vibration Measurement Cables.



Figure 3.25 Making Final Adjustments on J-52 Engine Installation.



Figure 3.26 J-52 Engine Ready for Testing.



Figure 3.27 Engine Operating Team Prior to J-52 Test.



Figure 3.28 Engine Operating Team After J-52 Test.



(a)



(b)

**Figure 3.29 (a) Making Final Hook-Up for F-404 Engine Test, and
(b) Video Recording for TV.**

3.4.3 Noise Monitoring and Instrumentation Plans

Jet engine noise was monitored at both near- and far-field sites. “Near-field” sites in the present context refers to those locations on the test pad that were 180 feet or less, from the center of noise production. In a more general context “near-field” refers to locations so close to the noise source that for some types of noise data analysis the physical extent of the noise source must be considered; i.e., one cannot consider the noise to be emanating from a point. In general, there is also a term “free-field” that assumes that the observer is sufficiently removed from a given noise source so that it can be considered a point source, but with the additional qualification that the measurement distance is not so great as to attenuate the noise by atmospheric absorption. “Far-field,” in general, refers to that portion of the noise field where the noise is considered to be emanating from a point and noise attenuation can occur as a result of both distance (a geometric dispersion) and by atmospheric absorption. In the present case, the near-field measurement points were located at both 90° (at a single position) and at 180°. In the latter case, the measurement points were every 10 degrees over a rear quadrant, from 90 to 180 degrees measured clockwise (see Figure 3.30). Stationary sound meters were placed at two positions, and a portable sound meter was carried to each of the remaining stations during each test sequence to measure noise levels. Far-field noise measurements (see Figure 3.13) were made at six locations for the J-52 engine, each 2 – 4 miles distant across the bay, and at two locations for the F-404 engine tests. All noise monitoring meters were set up and calibrated prior to the initiation of testing. Because of the many obstructions at the test site, only the one quadrant shown presented an opportunity for making acceptable “near-field” noise measurements. The far-field location of greatest interest, Solomons Island (2 miles distant), lay on an extension of a radii through the two stationary meters and provided a good opportunity for comparing near- and far-field results. Figures 3.32 through 3.34 show photographs of noise measurement locations and the noise measurement team.

Thermocouples, vibration sensors, and pressure transducers were installed to track gas temperatures at 16 locations, and vibration level and gas pressures at eight locations each, during testing of the J-52 engine (see Figure 3.31). But the intense vibrational environment set up within the NAD during the J-52 engine tests was so severe that the instrumentation sensors were all destroyed (or made inoperable) in the early phases of that testing. In fact, a purpose of the instrumentation had been to provide a record of actual test conditions if the NAD did structurally fail during testing. It turned out that the NAD was sufficiently strong, but the instrumentation was not. As no useful data was obtained from these sensors during the J-52 engine tests no attempt was made to attach any electronic / electrical sensors to the NAD for the F-404 tests. However, for the latter engine operational parameters were measured and recorded according to standard OETF operational procedures.

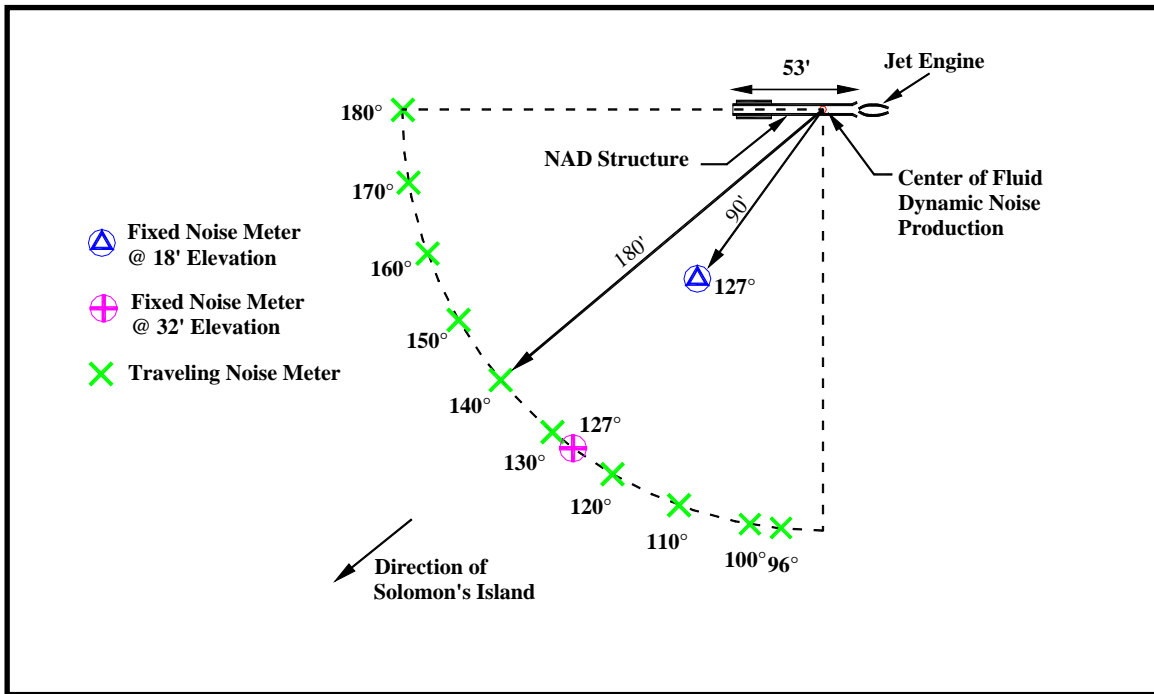


Figure 3.30 Diagram of Near-Field Noise Measurement Locations at OETF.

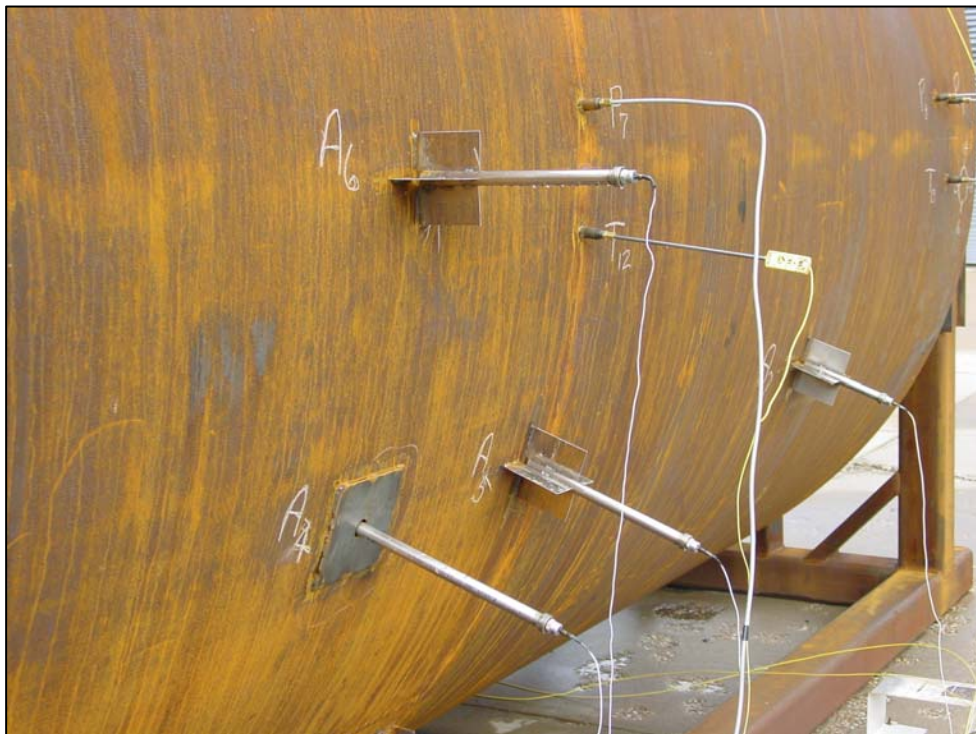


Figure 3.31 Accelerometer, Thermocouple, and Pressure Monitoring Sensors on Both Inner and Outer NAD Shells.



Figure 3.32 Photograph Showing Berm and Elevated Microphones (a) Single Stationary Microphone at 90' (right); and (b) Roving and Stationary Microphones at 180' (left).



Figure 3.33 Noise Monitoring Test Team Prior to Dispersing to Far-Field Noise Monitoring Sites.



Figure 3.34 Working Hard at a Far-Field Noise Monitoring Site.

3.4.4 Scheduling and Performing Test Operations

It had been estimated that the test time required for evaluating the performance of the NAD for an engine would be of the order of two weeks. In fact, it took almost three weeks for the J-52 engine tests (not including a delay caused by unsuitable weather conditions), but the total on-site test period for the F-404 engine was only six days. The test period involves: (a) installing the test engine; (b) conducting engine trial run-up tests and, when satisfactory, proceeding to make engine performance and noise measurements at the selected OETF and far-field measurement locations without the NAD in place; (c) installing the NAD along with its associated instrumentation on the test pad aft of the engine; (d) conducting engine run-up tests to ensure proper operation of the engine in conjunction with the NAD; (e) make engine performance and noise measurements at the selected locations as a function of engine power with the NAD in place; (f) review test results and repeat test points as required. Further details of the test procedures used for the F-404 engine, and of the specifications used for making the noise measurements are provided in Appendices A and B, respectively.

3.4.5 Operating Parameters for the Technology

The NAD must be designed to satisfactorily accommodate the exhaust plumes of the engines for which the NAD is intended for use. The limitation imposed upon use of the NAD is the maximum engine exhaust flow rate at maximum temperature for that engine. Because the NAD must be designed to accommodate the exhaust flow (volumetric rate of flow as well as high temperatures), a NAD designed for use with a large engine operating at after-burner would also be suitable for use with a smaller engine, but not the reverse.

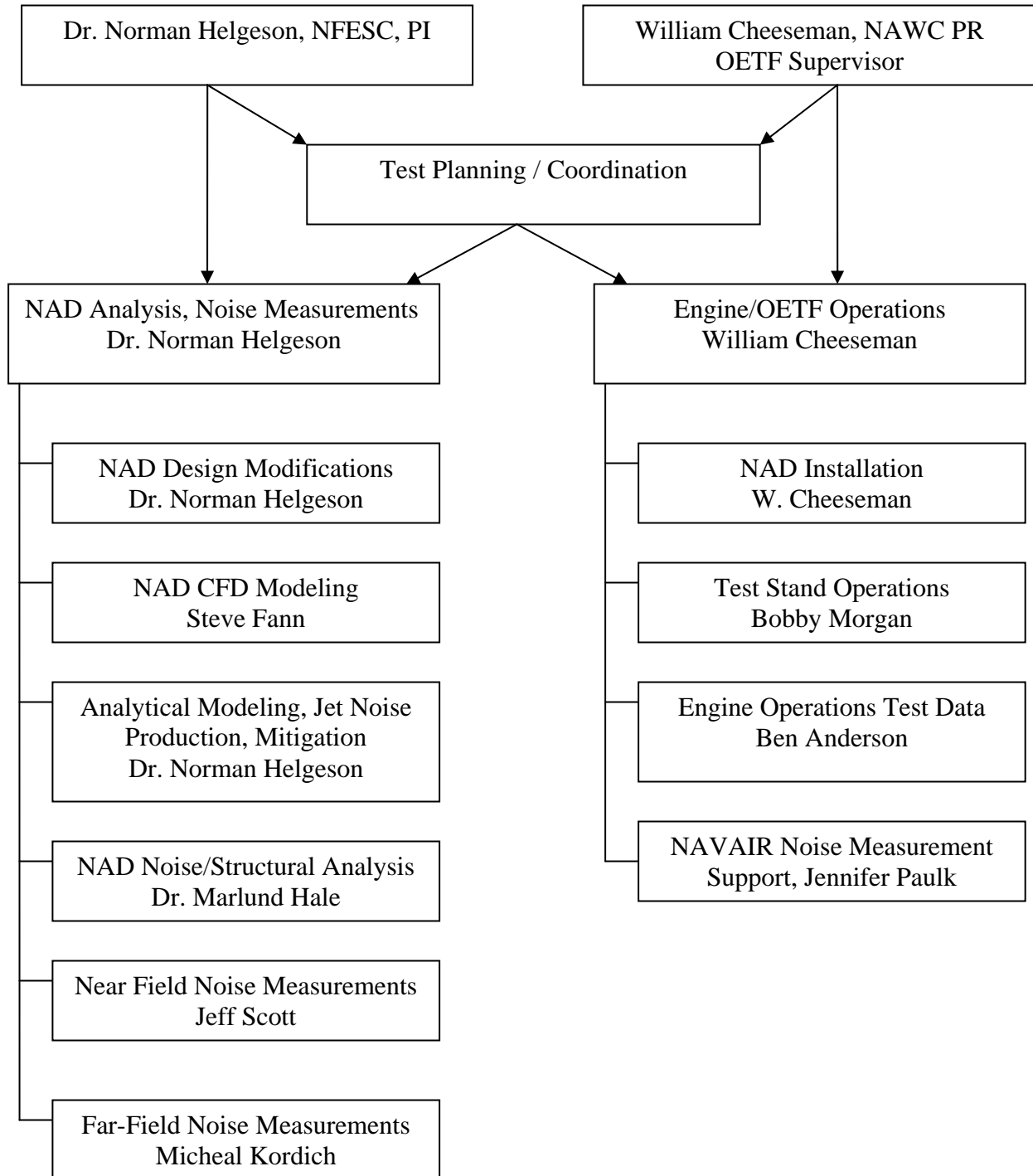
The NAD used for these tests was designed to accept the maximum engine exhaust flow for the F-414 engine (242 lbs. of exhaust gas per second at a temperature of 3800°F). It was designed using CFD calculations assuming these maximum flow conditions. As the flow conditions for the F-414 engine exceed those of both the J-52 and F-404 engines, the current NAD was also deemed suitable for the latter engines.

The NAD was installed and then tested at all engine power levels on which the engines are normally tested. The normal expectation would be that the NAD, once installed at a site, would remain installed and that other engines for which it is suitable could be interchanged for testing. That is, once it is installed, the cost for maintaining / operating the NAD would be very low. Maintenance costs would probably consist of daily (maybe twice weekly) checks for tightness of all bolts / connections of the NAD and a weekly vacuuming out of any debris that may have accumulated in the NAD. The latter is related to the problem of FOD (loose debris) that may accumulate in engine test areas and much care is always taken to try and eliminate any that could conceivably be drawn into the engine by the high velocity engine air intake flows.

3.5 Project Management and Staffing

The principle investigator for this project was Dr. Norman Helgeson. He was responsible for project oversight, coordination of NAD installation, noise measurements at the field test site, and analysis of the test results. Field testing of the NAD was performed under the direction of William Cheeseman, the OETF supervisor. The staff for field testing consisted of those involved in test set-up, engine operations, and acquisition of noise data. The test team was comprised of personnel from NAVFAC ESC, NAWC Patuxent River, and NSWC Dahlgren. CFD modeling was performed by Steven Fann and acoustic and structural interaction consultation was provided by Dr. Marlund Hale of Advanced Engineering Acoustics. Project staffing relationships are shown on Table 3.1.

Table 3.1 Project Staffing Relationships



4.0 FIELD TEST RESULTS

In proceeding to full-scale field-testing of the NAD with the F-414 engine, NAWC PR test personnel determined that testing of the NAD should be approached in steps: (a) first test the NAD on the older J-52 engine (which has no after-burner but has mass flow rates similar to that of the F-414 engine), (b) evaluate the NAD using the F-404 engine (which has an after-burner but is a little smaller than the F-414 engine), and (c) assuming that testing with the two previous engines had been satisfactory, move forward to testing the NAD with the F-414 engine. Steps (a) and (b) of this test sequence are described and reported on here. Step (c) will be performed during an ESTCP project that is underway.

Noise measurements were made at near- and far-field measurement locations for the engine at several power levels both with and without the NAD in place (see Section 3.4.4). Comparison of these results provided the data needed for determining the noise reduction capability of the NAD. The data were then analyzed and evaluated to show both overall dBA noise reductions and noise reductions as a function of frequency.

4.1 Field Test Results for the J-52 Engine.

4.1.1 Results of Noise Measurements

Near- and far-field noise monitoring sites were described in Section 3.4.3. Figures 3.11 and 3.13 showed overhead views of the NAWC PR test site and Figure 3.30 showed the OETF noise meter locations. Two stationary noise meters were used at the OETF site, along with a roving meter that was used to obtain noise measurements along a 180-foot radius. The two stationary meters ran continuously during testing while readings along the 180-foot radius were obtained in a series of 15-second sound bites, one at each location, for each engine test condition. Because of the many obstructions at the test site (see Figures 3.11 and 3.12) only this one quadrant presented an acceptable opportunity for noise measurements. Far-field noise measurements were made at six sites 1 - 4 miles distant from engine operation, but the far-field location of greatest interest, Solomons Island (2 miles distant), lay on an extension of a radii through the two stationary meters and provided good opportunity for comparison of near- and far-field results.

The near-field broad-band sound pressure levels for 85% and military (100% without after-burner) engine powers and the insertion losses (i.e., net noise reduction, in decibels obtained by the use of the NAD) are shown on Figures 4.1 – 4.3 as a function of angular position for three NAD end-piece configurations (see Figures 2.1 and 3.18 – 3.23 for end-piece illustrations). The results (Figure 4.1) for military power for the NADa (Figures 3.20 and 3.21) and NADb (Figures 3.22 and 3.23) configurations showed similar noise attenuations (a peak of about 10.dBA noise attenuation). However, noise attenuations at 85% power for the NADb and NADc (Figures 4.2 and 4.3) configurations were significantly different, showing a significant increase in noise attenuation with increased flow restriction by the cone end-piece (NADc). The attenuations reached a maximum of about 18.5 dBA (Figure 4.3) for the NADc (cone) configuration with greater attenuations expected for greater (i.e., at military) power. However, because re-ingestion of engine exhaust into the engine had been observed at 85% power (see Table 4.1) with the NADc configuration, it was decided that testing of the NADc at military power could not be conducted until the re-ingestion problem was corrected.

The far-field broad-band results for these tests showed noise reductions of 13.5 dBA (see Figure 4.4) at military power. A review of those results shows an increasing capability of the NAD to reduce noise as engine power is increased from idle to 100% (military) power. Reasonable extrapolation of these results indicate that, for the far-field, greater noise reductions may be achievable at higher engine powers (e.g., at after-burner conditions). These results, obtained over a two-day test window, were considered encouraging and potentially important in smoothing relations between NAWC PR and the surrounding communities (Reference 3).

Spectrums of the noise measured at the near field and at the Solomon Islands far-field site are shown in Figures 4.5 and 4.6. These spectrums are from measurements made with the engine operating at military power for both the baseline (i.e., no NAD) and for the NADa and NADb configurations.

Figure 4.5 shows the noise spectrum from the stationary meter at 90'. At an elevation of 18 feet above ground level, this meter probably had the best (least physical obstructions) near-field view of the noise source. Frequencies are recorded in 1/3 octave intervals from 12.5 to 20,000 Hz. The magnitudes of the noise recorded at each frequency interval is according to the L (linear, i.e., uncorrected for a bias of human hearing) scale (dBL). At each frequency interval a magnitude is provided for each test configuration: baseline and for NADa and NADb. For each 1/3 octave the magnitude of the baseline noise intensity is consistently greater than that for the NADs, ranging from differences of about (+)12. dB at 12.5 Hz, to (-) 3. dB at 40 Hz, to (+) 15. dB or more at higher frequencies. Broad-band integrated averages of these spectral results are shown at the far right for both the A and L scales, and show broad-band noise reductions of 12. – 13. dB. The results show good attenuation across the spectrum, except for the region of about 40 Hz. We have no good explanation for the loss in effectiveness of the NAD in that part of the spectrum, except that this frequency is close to what was determined prior to field testing as the natural frequency (60 – 70 Hz) of the NAD pipe segments. That is, elements of the NAD could have been set in motion by the jet exhaust, despite stiffening reinforcements included in the design, to lessen the effectiveness of the NAD at those frequencies. Other than that, the broad spectrum of NAD effectiveness – from a low of 12.5 Hz – was encouraging.

Figure 4.6 shows spectrum results for the Solomon Islands far-field site (measurements were made at this site by both Navy and State of Maryland personnel, the results being similar), and the spectrum here is monitored down to 6.5 Hz. The disappearance of the noise levels at frequencies above 1000 Hz at the far field is due to the well-known phenomena that low-frequency noise travels much more effectively over long distances than does high frequency noise because of the greater absorption of high frequency sound energy by the atmosphere. In this case noise intensities are plotted from 20.dB (which is at about the lower limit of human hearing) to 80 dB. These measurements show a broad-band effectiveness of the NAD in reducing noise extending from the very low to the very high frequencies.

In summary, (i) significant broad-band noise reductions were recorded at idle, 85% and 100% engine power levels, (ii) both near- and far-field data support the conclusion that

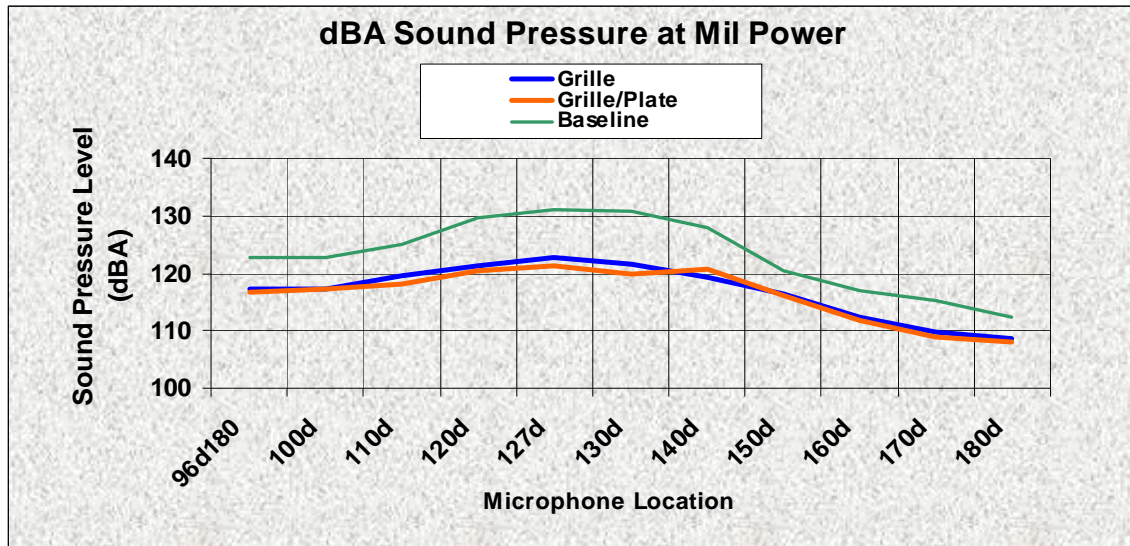


Figure 4.1 Near-Field Sound Pressure Measurements for NADa and NADb Configurations at Military Power.

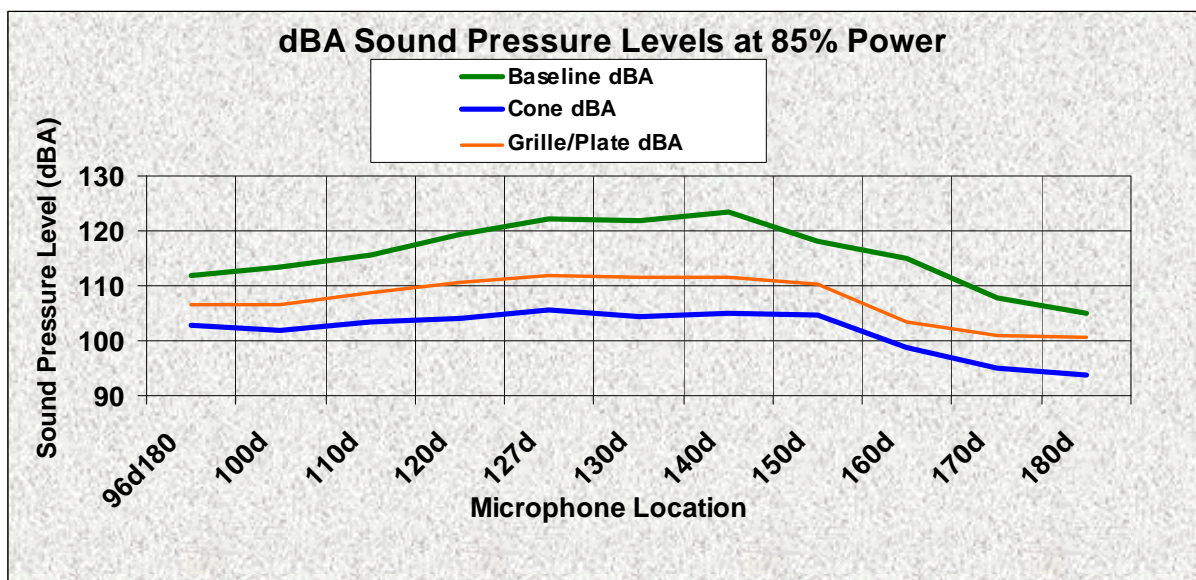


Figure 4.2 Near-Field Sound Pressure Measurements for NADb and NADc Configurations at 85% Power.

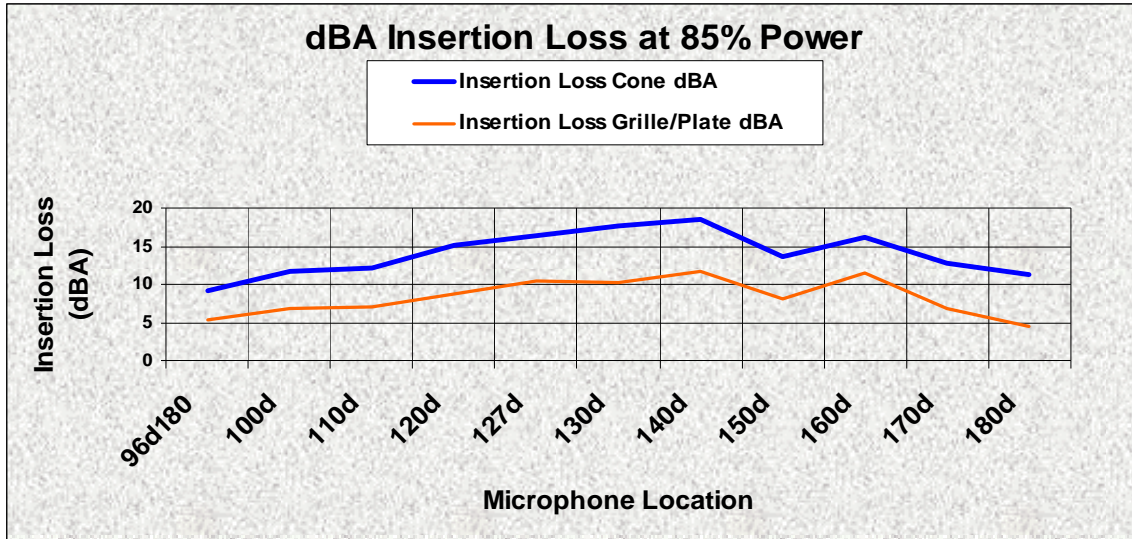


Figure 4.3 Noise Insertion Losses for NADb and NADc Configurations for J-52 Engine Operating at 85% power.

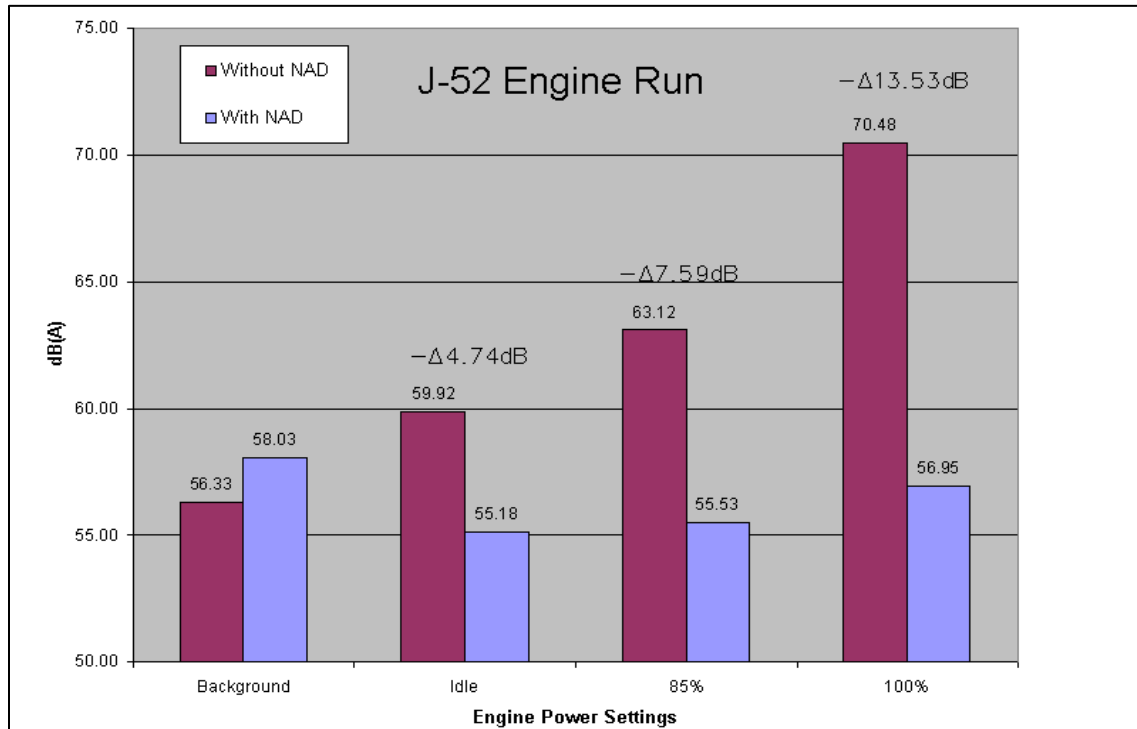


Figure 4.4 Results of Far-Field Noise Measurements at Solomons Island (2 miles distant) with/without NADa for J-52 Engine.

Table 4.1. Observed Re-circulation of NAD Exhaust Gases to J-52 Engine During Field Testing of NAD Configurations a, b, and c

Engine Power Level	NADa (grille)	NADb (grille + plates)	NADc (cone)
Idle	No	No	No
85%	No	No	Yes
100%	No	No	Test Cancelled

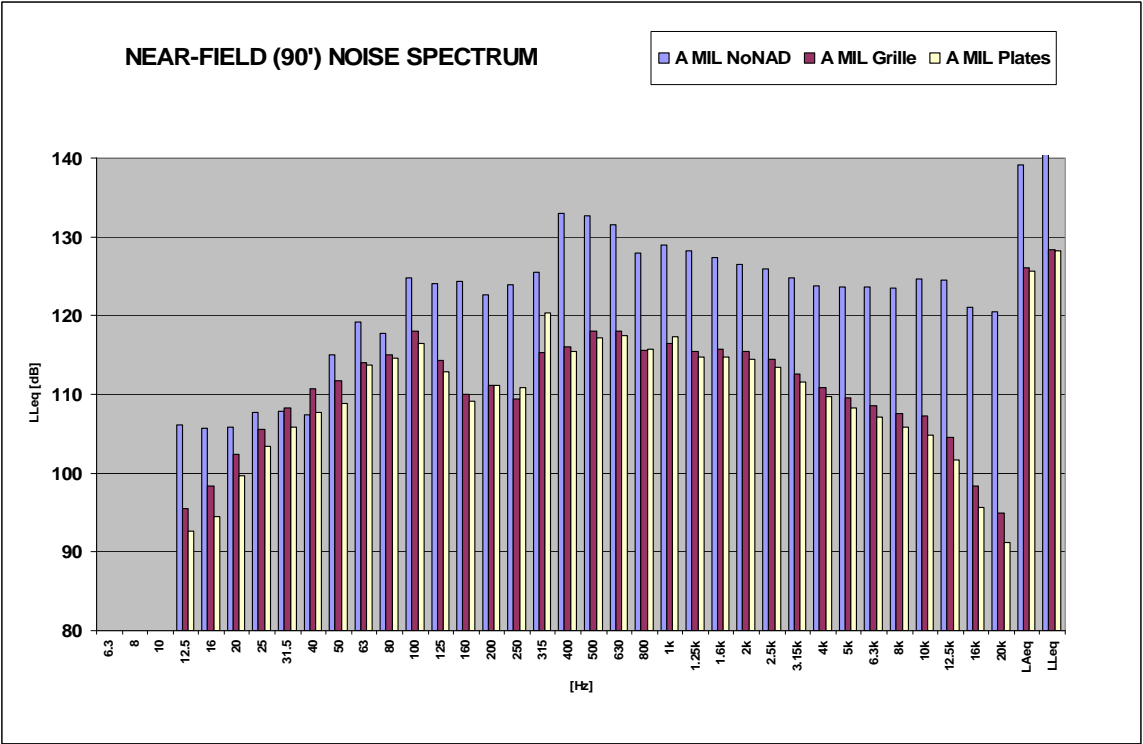


Figure 4.5 Near-Field Noise Spectrum for J-52 Engine Operating at Military Power With/Without NAD for Baseline and with NADa and NADb Configurations.

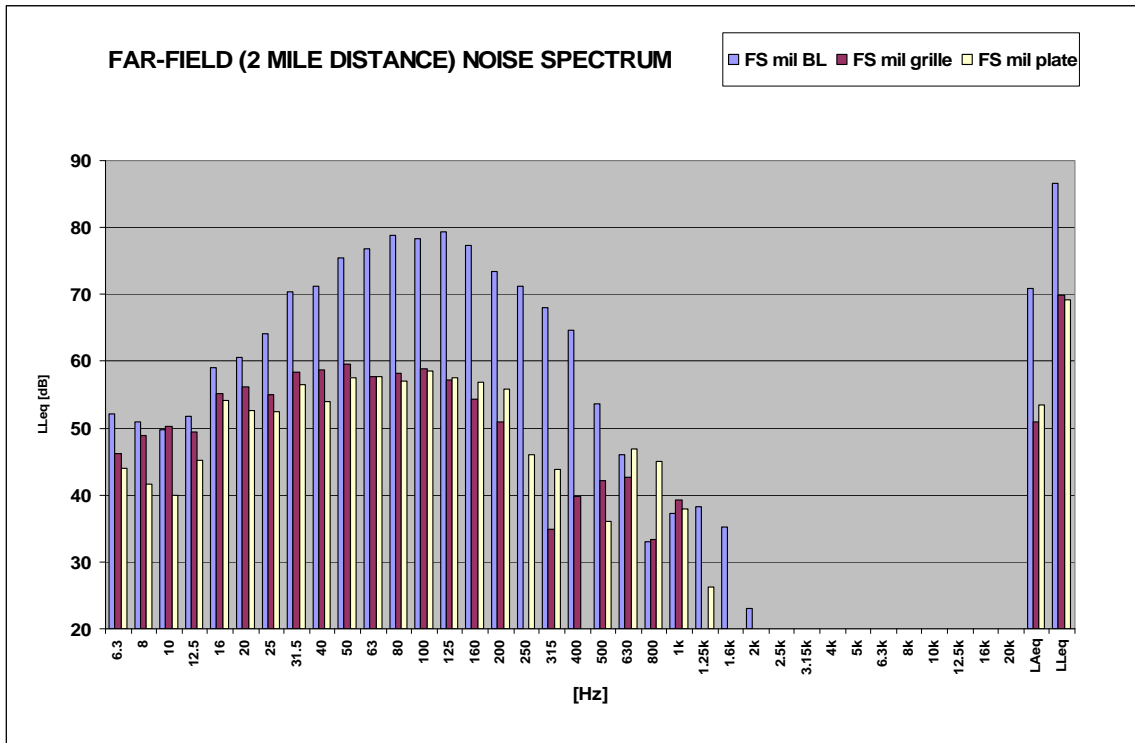


Figure 4.6 Far-Field Noise Spectrum for J-52 Engine Operating at Military Power With/Without NAD for Baseline and NADa and NADb Configurations.

noise attenuation by the NAD is broad-band from the low to the very high acoustic frequencies, and (iii) attenuation of the low-frequency components of the noise by the NAD appears to effectively limit the transmission of these low frequency components to the far field, as reflected by the far-field acoustic spectrum. Further NAD design refinements (e.g., additional structural stiffeners) could lead to improvements in noise reductions in the 40 – 50 Hz frequency range.

4.1.2 Exhaust Flow Recirculation To Engine Inlet.

The recirculation of NADc exhaust gases to the engine inlet during the J-52 engine tests at 85% engine power, as described in Table 4.1, was an unacceptable result that needed to be corrected before further tests could be undertaken.

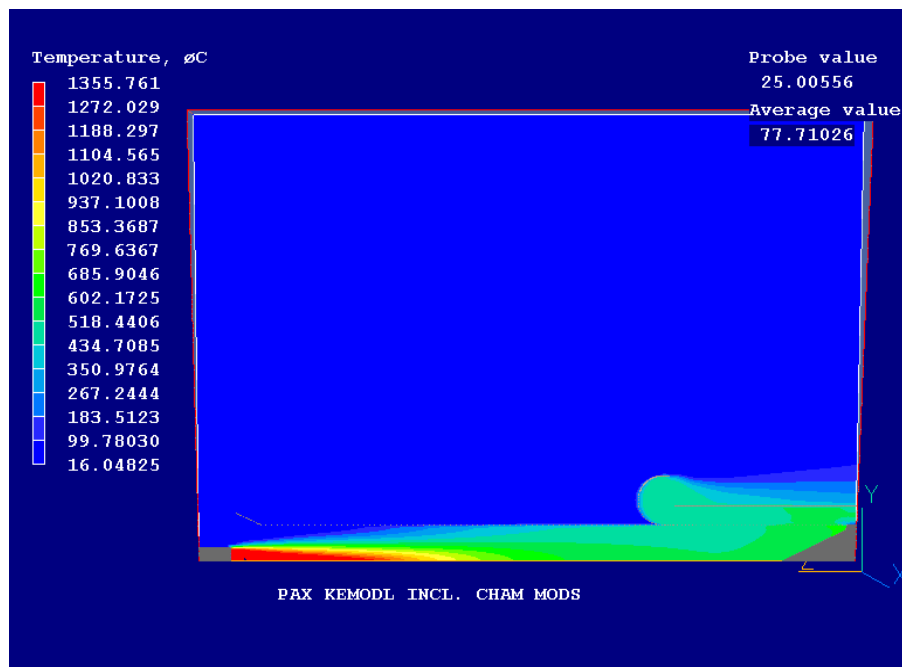
4.2 Field Test Results for the F-404 Engine

Recirculation of NAD exhaust gases to the engine inlet during the J-52 engine tests was an unacceptable result that needed to be corrected before further NAD testing could be undertaken with the F-404 engine. It was determined that a flow deflector that could be added at the front end of the shroud (the outer annular tube) would be designed and installed to eliminate this problem.

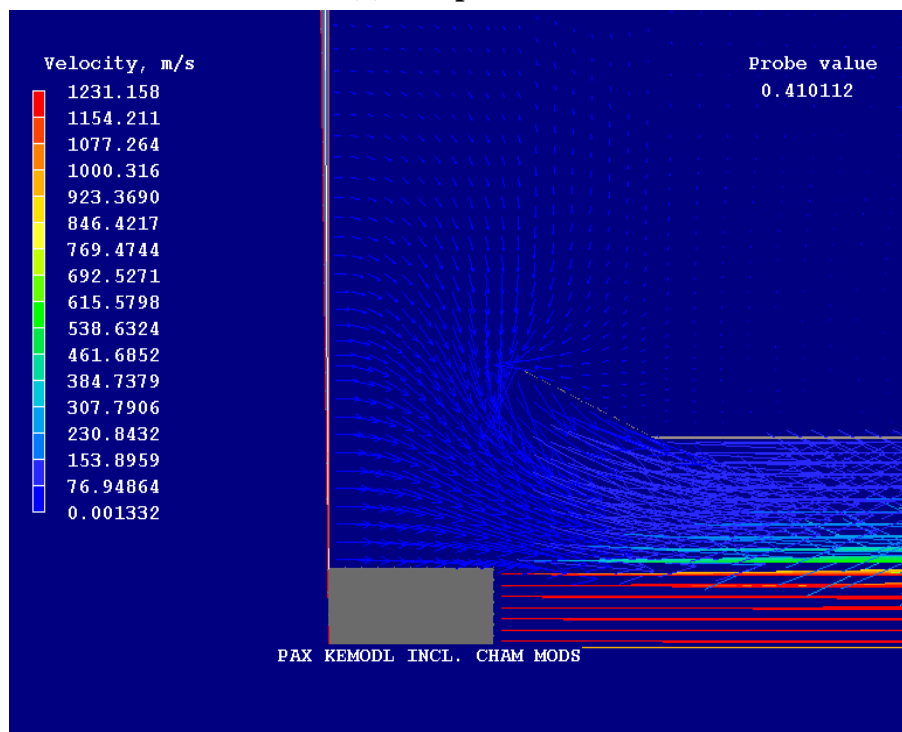
4.2.1 CFD Analysis, Design and Installation of Flow Deflector.

To address this problem NAVFAC ESC acquired a PHOENICS CFD program to further study the fluid dynamics of the NAD flow field. CFD boundary conditions were reviewed and revised,

and efforts were undertaken to prepare an optimum fluid dynamic design and flow path for designing and fabricating a NAD flow deflector. Results of that CFD analysis are shown in Figure 4.7

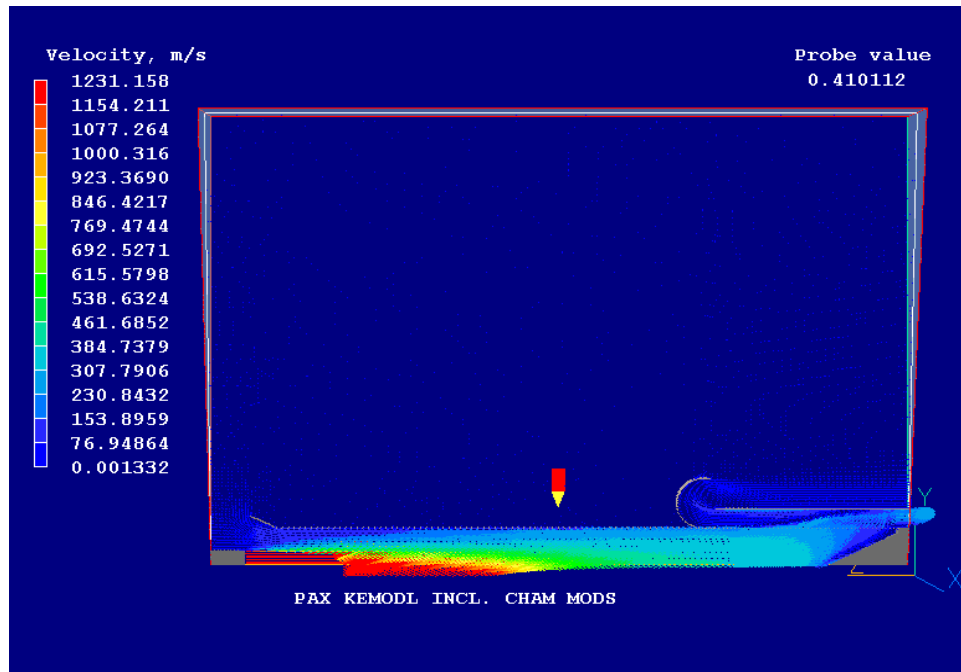


(a) Temperature

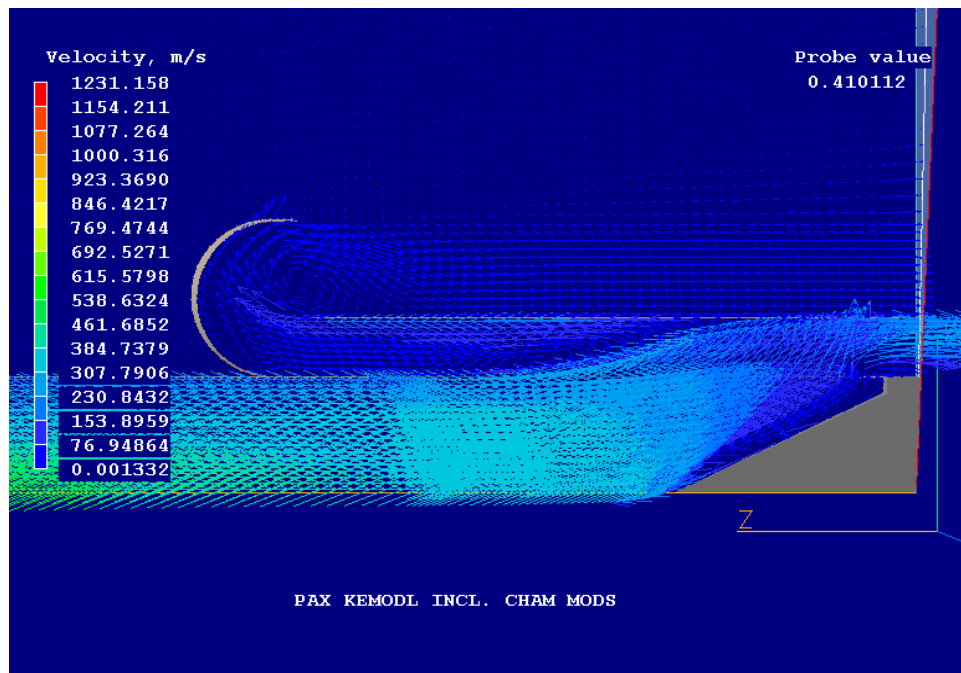


(b) Inlet Velocity Field

Figure 4.7 NAD/Flow Deflector CFD Results.



(c) Overall Velocity Field



(d) Outlet Velocity Field

Figure 4.7 NAD/Flow Deflector CFD Results (continued).

The outline design of the flow deflector (in three pieces) is shown in Figure 4.8 and its field installation is shown in Figures 4.9 and 4.10.

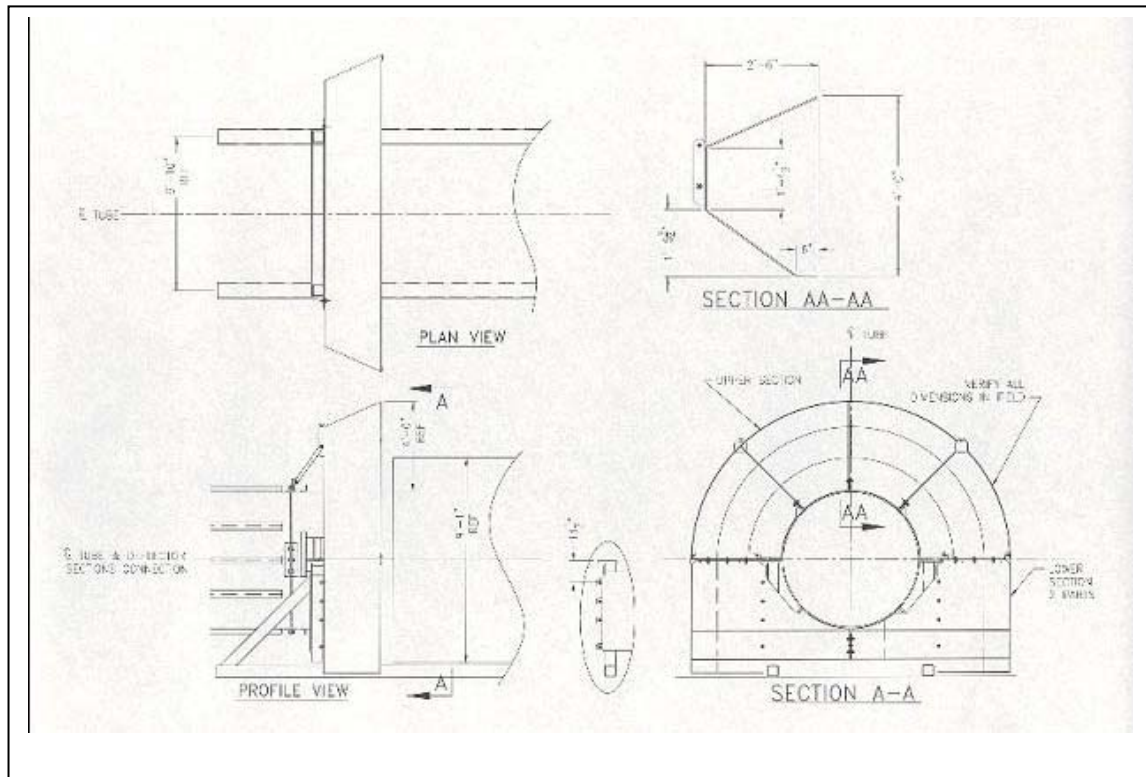


Figure 4.8 Outline Drawing of Flow Deflector: (a) Top Central Piece, and (b) Two Side Lower Pieces for Field Installation.



Figure 4.9 Installing Top Central Piece of Flow Deflector.



Figure 4.10 Installing Lower Side Piece of Flow Deflector.

4.2.2 F-404 Field Test Noise Measurements

4.2.2.1 Near- and Far-Field Noise Insertion Losses. Field tests of the NAD / Flow Deflector with the F-404 engine were completed for engine power levels up to and including after-burner, proving the adequacy of the flow deflector for properly directing the NAD exhaust flows. Noise measurements were recorded at five engine power levels from idle to max after-burner. As for the J-52 engine, these measurements showed increasing NAD noise reductions with increasing engine power in both the near- and far-field, reaching total noise reductions > 20 dBA (at both locations) at after-burner conditions. The variations in noise “insertion loss” with engine power are shown on Figures 4.11 (near-field) and 4.12 (far-field). The insertion loss for the near-field (90 feet from NAD) reached a maximum of 20.6 dBA at maximum after-burner power, and a maximum of about 34 dBA at the far-field site at maximum after-burner. However, some discussion in regard to the “background noise” that was measured at the far-field site and which becomes part of the calculation of the “insertion” loss is appropriate, and included below.

4.2.2.2 Background Noise measurements. Knowledge of “background noise level” was important in determining the “insertion losses” (i.e., the net noise reduction due to use of the NAD) at the far-field site for both the J-52 and F-404 engine tests (see Figures 4.4 and 4.12). Background noise was unimportant for the near-field site because the engine noise was so great that the background noise became insignificant. For example, for the J-52 engine, Figure 4.4 shows that the “background” noise measurements taken at the far-field site, with / without the NAD in place and the engine not running, were quite close (56.3 and 58.0 dBA), as would

normally be expected. Comparing those “background” values to the far-field noise levels measured with the engine operating and with the NAD in place, the measured noise levels were 55.2 dBA (with engine at idle), 55.5 dBA (with engine at 85%), and 56.9 dBA (with engine at 100% power), see Table 4.2. That is, the measured noise remained almost constant and at essentially “background” levels for all engine powers tested. Therefore, the conclusion was that these measurements probably represented “background noise,” and that only an insignificant and unidentifiable portion of the engine noise generated when the NAD was in place reached the far-field site. The arithmetic average of the “background “ noise for these five measurements is 56.4 dBA.

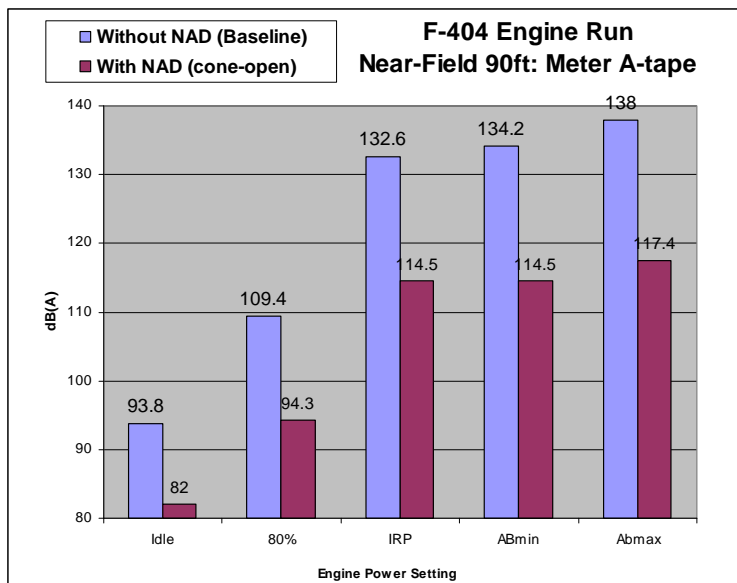


Figure 4.11 Results of Near-Field Noise Measurements With/Without NAD for F-404 Engine.

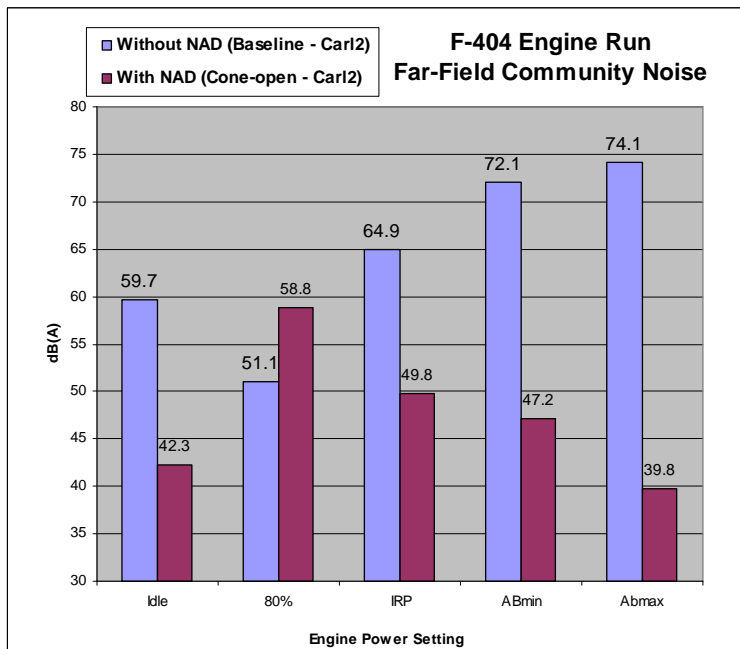


Figure 4.12 Results of Far-Field Noise Measurements at Solomons Island (2 miles distant) with/without NAD for F-404 Engine.

Table 4.2 J-52 NAD Test – Background Noise Data

Time: Pre-Test	Level:
NAD Configuration (Engine not Running)	56.3 dB
Baseline	58.0 dB
Engine Idle with NAD	55.2 dB
Engine at 85% with NAD	55.5 dB
Engine at 100% with NAD	56.9 dB

For the F-404 engine at the far-field (see Figure 4.12), however, there is a wide variation in the measurements of what could be considered “background” noise. These values varied from 39.8 (almost an especially quiet moment significantly less than a normal day-time background noise level) to 58.8 dBA (a more typical day-time background noise level, but less than human conversation).

The magnitude of ambient (or background) noise rises and falls throughout the day and night, depending upon close-by human activity. Therefore the momentary magnitude of the background noise can vary between a high average and a low average. For example, a low-flying jet aircraft in the flight pattern of aircraft taking off from the adjacent NAWC PR, and passing overhead of the far-field site, would cause a momentary high average. To help understand the significance of these measured background noise levels, they can be compared, roughly, to the magnitudes for: a quiet urban nighttime – 40 dBA; a quiet urban daytime – 50 dBA; the sound level of conversation - 64 dBA; or, on this logarithmic scale, to a jet engine at 100 feet at about 130.0 dBA. So it can be seen that the variation of “background noise levels” as reflected by the reported background measurements (between 40.0 dBA and 60.0 dBA) is not great when compared to the variation of noise levels as one normally experiences them.

Tables 4.3 and 4.4 show measurements of “background noise” made during testing of the F-404 engine. In Table 4.3, results are shown for background measurements over two periods of time of approximately 17 minutes each, before and after an engine test. The average noise measurements for those two periods are 56.4 and 61.9 dBA. However, if each of those time intervals is broken first into two intervals, and then into four intervals, seven of the resulting eight interval values are between 54.5 and 58.9, similar to the results for the J-52 test in Table 4.2. As the measurement of 66.6 dBA is uncharacteristically high, and because of the known variability of the background (e.g., low flying aircraft directly overhead), it seems reasonable to exclude that as an aberrant value, probably due to aircraft overflight or other local activity. The arithmetic average of the remaining seven values is 56.7 dBA. Table 4.4 shows only a single value of 55 dBA for background noise. This is because the noise meter for this test was mistakenly set to record only noise levels at 55.0 dBA and above. Therefore, during most of this period, no data was recorded, showing that noise levels were actually less than 55.0 dBA.

However, a value of 55.0 dBA was recorded during one small time interval showing that a value of 55.0 dBA was the probable maximum background noise for that period.

If we consider other far-field noise measurements that were recorded with the NAD in place, Figure 4.12 provides the values of 42.3, 58.8, 49.8, 47.2, and 39.8 dBA, all recorded over a time span of less than one and one-half hours. Although the readings showed a significant variation of background noise, all measurements were all within the range of what might be considered a “normal urban background noise level.” Therefore, lacking other evidence, it is assumed that that is what they represent.

Table 4.3 F-404 Baseline Background Noise Data – Aug. 18, 2006

Time: Pre-Test	Duration: 17min 24 sec / Level:	Duration: 8min 54 sec / Level:	Duration: 4min 24 sec / Level:
Aug 18, 10:28:37 hrs	56.4 dB	56.7 dB	55.9 dB
To		56.0 dB	57.2 dB
Aug 18; 10:46:01 hrs			55.4 dB
			56.7 dB
Time: Post-Test	Duration: 16min 59 sec	Duration: 8min 54 sec	Duration: 4min 24 sec
Aug 18, 11:28:11 hrs	61.9 dB	64.1 dB	58.1 dB
To		57.2 dB	66.6 dB
Aug 18; 11:45:10 hrs			54.5 dB
			58.9 dB

Table 4.4 F-404 NAD Cone-Open Background – Aug. 16, 2006 (Meter Lower Limit Setting: 55 dB)

Time: Pre-Test	Level:	Time: Post-Test	Level:
Only a small portion of data points are above 55 dB.	55 dB	Only a small portion of data points are above 55 dB.	55 dB

Therefore, adding all legitimate background values (56.3, 58.0, 55.18, 55.53, 56.95, 7 x 56.7, 55., 42.3, 58.8, 49.8, 47.2, and 39.8 – excluding only the 66.6 value), and dividing by 18, an arithmetic background average 54.dBA is obtained. It must be remembered, however, that although these values all appear to be typical background levels for characterizing the far-field site, the actual background level that exists at that location “during an engine test” without the NAD in place remains indeterminate. That is, it can be only estimated on the basis of far-field noise measurements made when the engine is not running, with or without the NAD. With the NAD in place, the “background noise” can be no greater than that measured during the test at the far-field site. For example, 39.8 dBA at maximum after-burner (Figure 4.12) represents the maximum background noise at that time. It also represents the maximum possible noise reaching the far-field site from the operating engine and background combined.

With the above in mind, the “background noise” at the far-field site was typically of the order of 55.0 dBA, but may have been lower, extending to as low as 40.0 dBA.

4.2.2.3 Near- and Far-Field Noise Spectrums. Noise spectrums with / without the NAD in place are shown for the frequency range of 6 to 20,000 Hz in Figures 4.13 and 4.14 for the near- and far-fields. The ordinates on these plots are shown as LLeq. Each of the one-third octaves on these plots (e.g., from 12.5 Hz to 25 Hz is an octave, i.e., a doubling of the frequency - this octave is divided up into thirds with the centers at 12.5, 16, and 20 Hz) has an Leq associated with it. But the Leq value for each 1/3 octave spectrum element is plotted without applying the A weighting factor. Therefore that number has a dBL (unweighted) value. On the far right hand side of each plot all of the 1/3 octave values have been logarithmically added to provide total Leq's summing up the effect of the entire range of frequencies – i.e., a total Leq. These total Leq's are given in both dbA (A) and dBL (L) values, depending upon whether an A weighting factor was applied or not.

It is these overall Leq's that are referred to when it is said that overall noise reductions were 20. dBA. For example on Figure 4.13, the difference of Leq(A) with / without the NAD, is 138. – 117. dBA, or 21. dBA. For the L scale Leq is 143. – 120. dBL, or 23. dBL. On Figure 4.14 for the far field, these differences in the overall Leq's with / without the NAD were 35. dBA and 19. dBL.

4.2.2.4 Effect of Atmospheric Conditions on Far-Field measurements. Weather and atmospheric conditions, unless the conditions are so severe that use of the NAD (or even static engine test-stand testing) may be impractical, will have little effect on noise measurements made in the “near-field.” However, the effect of weather and atmospheric conditions on far-field measurements can be substantial. Low cloud ceilings and temperature and humidity gradients can serve to bend / refract sound waves, and sometimes provide a propagation channel for the long-range transmission of low-frequency noise. Changes in humidity and temperature also change the sound absorption properties of the atmosphere. Wind can be a major help / hindrance in the propagation of sound waves, and natural barriers (hills and vegetation) serve to deflect and absorb sound energy. Therefore, when evaluating NAD performance, all of these factors must be considered.

The effect of atmospheric absorption of sound energy is illustrated dramatically in comparing the spectrums for the near- and far-fields in Figures 4.13 and 4.14. The near-field spectrum is for data measured approximately 90 feet from the noise source. At this distance there is little chance that significant absorption of sound energy can occur between the noise source (the jet exhaust plume) and the measuring instrument. Sound energy was transmitted over the full range of frequencies reported (6.5 – 20,000 Hz) to the near-field monitor. On the other hand, little of this sound energy was recorded at the far-field site at frequencies greater than about 500 Hz. That is, the high frequency noise was absorbed by constituents of the atmosphere so efficiently that little of it reached the far-field site. The low frequency noise was also attenuated during its travel to the far-field monitoring site, but less efficiently than the high frequency components. Thus atmospheric absorption selectively reduces the intensity of the high frequency sound waves at the far-field site.

Wind has a different effect on noise transmission. It affects all frequencies to the same degree and may thus lead to higher, or lower, Leq (summation over all frequencies), depending upon whether the wind is following or ahead. Because it is difficult to estimate the quantitative impact that these varying atmospheric/weather conditions may have on any particular set of measurements, it is desirable to conduct tests where the results will be compared under as similar conditions as possible. To date, that has been possible with comparison measurements for the J-52 being made on adjacent days when the weather conditions were very similar, and for the F-404 engine when the comparison measurements were made during the same half-day with little change in conditions.

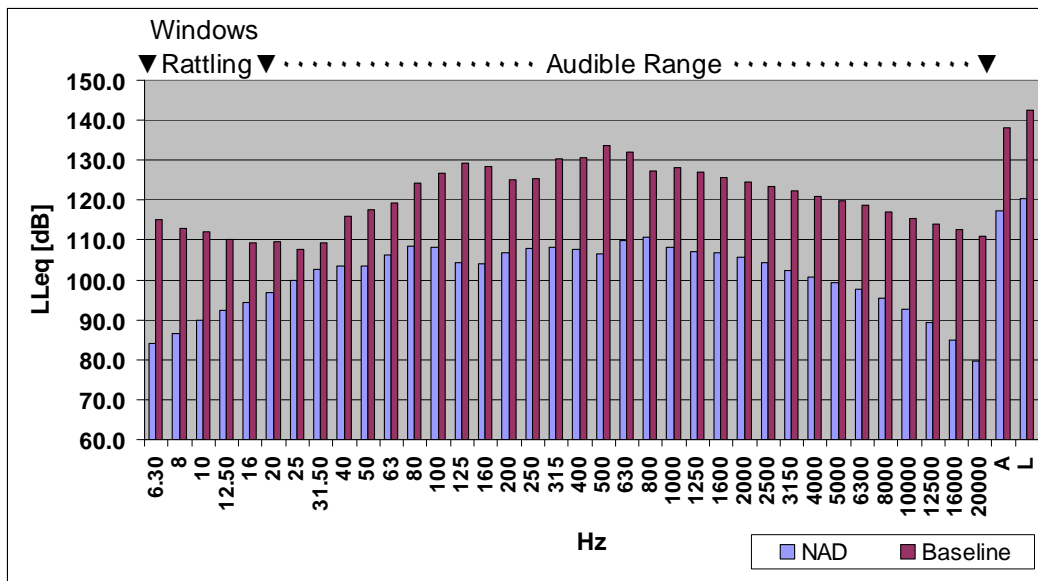


Figure 4.13 Near-Field Noise Reductions with NAD and F-404 Engine @ afterburner at a distance of 90 feet.

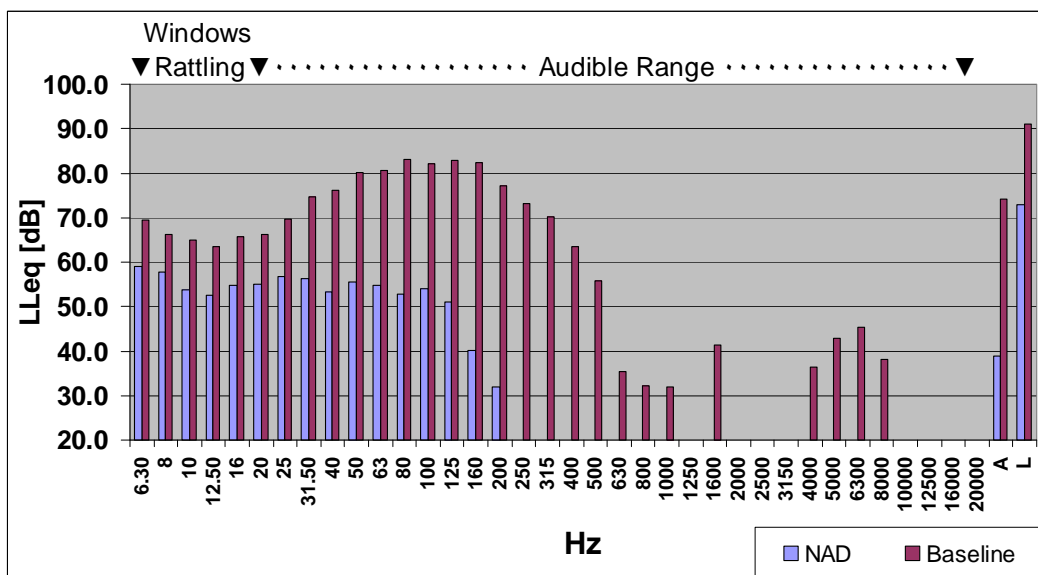


Figure 4.14 Far-Field Noise Reductions with NAD and F-404 Engine @ afterburner & 2 miles.

4.2.3 Flow Deflector and F-404 Engine Test Results

With the flow deflector installed it was possible to proceed to F-404 engine testing at military and after-burner engine power levels with no indication of re-ingestion of engine exhaust into the engine. That particular issue was completely resolved by installation of the flow deflector. No appreciable increase in engine air inlet temperature was detected that could be attributed to the recycling and re-ingestion of engine exhaust gases at any power level up to and including maximum after-burner. A further issue that had been raised at times was the effect that the NAD might have on engine performance. Previous CFD calculations and sub-scale test measurements had both indicated that use of the NAD would have no effect on engine performance. However, this had remained a concern for some in applying the NAD to a full-size jet engine. Measurements of the engine pressure ratio (EPR) of the F-404 during NAD testing at military power showed there to be no measurable difference in recorded engine data whether the NAD was or was not in place behind the F-404 engine.

4.3 Test Summaries and Conclusions

4.3.1 Test Results From the J-52 Engine

Testing of the NAD with the J-52 engine showed:

- a. Significant total (integrated over all frequencies) noise reductions at idle, 85% and 100% engine power levels. Noise reductions increased with engine power and reached a maximum of 13.5 dBA with the NADb configuration at 100% power.
- b. Tests could not be conducted at military power with the NADc (cone end-piece) configuration because of ingestion of exhaust gases into the engine at 85% power. Even so, the test results at 85% power showed an impressive noise reduction of 18.5 dBA with the NADc configuration, and showed the effectiveness of increasing blocking of the NAD exit area to increase noise attenuation.
- c. Both near- and far-field data supported the conclusion that noise attenuation by the NAD is broad-band from the very low (6 Hz) to the very high (20k Hz) acoustic frequencies. Attenuation of the low-frequency components of the noise by the NAD appears to effectively inhibit the transmission of these low frequency components to the far field, as reflected by the far-field acoustic spectrum. The high frequency noise components were almost completely attenuated by atmospheric absorption prior to their reaching the far-field site so that at frequencies above 1000 they were not measureable above 20.0 dBA.
- d. The problem of exhaust gas re-ingestion into the engine with increased blockage of the NAD end-piece became a concern that required resolution prior to testing of the NAD with the F-404 engine.

4.3.2 Test Results From the F-404 Engine

Testing of the NAD with the F-404 engine showed:

- a. The exhaust flow deflector that was designed and fabricated prevented exhaust flows from re-circulating to the engine intake and made possible testing of the NAD at all engine power levels up to and including maximum after-burner (see Section 4.2.3).

- b. The broad-band noise attenuation observed during the J-52 engine tests (see Figures 4.5 and 4.6) was fully corroborated by the results from the F-404 tests (see Figures 4.13 and 4.14). The effectiveness of the NAD in attenuating low-frequency noise, down to the very low frequency of 6.5 Hz, is encouraging and extremely important as attenuation of such low-frequency noise is the most difficult to achieve. Attenuation of high-frequency noise was also effective, but as demonstrated in the tests, this noise was largely absent at the far-field site because of atmospheric absorption.
- c. The continued improvement in total noise attenuation (21. dBA for the near-field and 35 dBA for the far-field) for the F-404 engine is in accordance with projections of NAD performance as measured for the J-52 engine. Tests of the latter showed (see Figure 4.4) increased noise attenuation by the NAD at greater engine power levels. This trend continued with the F-404 engine tests and is an indication that the steps being taken to increase the effectiveness of the NAD noise reduction are working and that further improvements can be anticipated.
- d. Verification that the presence of the NAD at the rear of the engine has no measureable effect upon jet engine performance (as measured by its engine pressure ratio, EPR, at military power) answered a question that had concerned several (See Section 4.2.4) regarding application of the NAD to full-scale engines.

5.0 TECHNOLOGY INTEGRATION

5.1 Costs

5.1.1 Fabrication Costs

The cost of fabricating an NAD is approximately \$250k compared to \$12M to \$15M for the construction of a new JETC. Therefore savings for the installation of just one NAD in the place of a JETC would be in excess of \$12M. Aside from direct dollar savings are cases where large sums of money needed for construction of a JETC (or hush-house) would simply not be available - or not available for an extended period of time. The inexpensive NAD could play an important role in situations where the noise issue is important, and which could otherwise cause the curtailment of aircraft operations and /or engine testing schedules.

Assuming carbon steel construction and no fundamental change to the design approach used for the current NAD, the cost basis and cost driver for the NAD is the size and thermal loading of the jet engine for which the NAD is designed. Size refers to a combination of physical size (i.e., diameter of the engine), hot gas through-put (lbs/second), and the maximum temperature of the exhaust stream. A physically larger-sized engine will require a larger-diameter NAD, and the temperature and volume of the jet exhaust may also require a larger-diameter NAD. Therefore the cost of fabrication of the NAD will increase approximately proportional to $D^{1/2}$ (Reference 4) times an escalation factor. The base cost of comparison is the current NAD (6 foot inlet diameter), designed for the F-414 engine.

5.1.2 Activity Costs

The projected NAD activity costs are shown in Table 5.1. Costs associated with acquiring an NAD include those for: startup/site assessment, NAD purchase cost, installation costs, personnel

training, and maintenance costs (cleaning of NAD, mechanical upkeep, inspections). The procedures used for estimating the costs as well as the summary values are shown.

Table 5.1 NAD Activity Costs

NAD Activity Costs		
Startup/Site assessment - 2 NAVFAC ESC employees - 3 days on travel	\$8,500	
Permit costs - No permitting required for device	\$0	
Equipment purchase - Per PI	\$250,000	
Equipment installation - 3 NAVFAC ESC employees, 7 days travel	\$26,000	
Training - 1 NAVFAC ESC employee 3 days travel - 3 local employees 1 day training	\$5,000	
Maintenance	\$13,000	year
Replacement Costs	\$250,000	per item
Disposal - Cost to remove from site	\$8,000	One time end of life
Overall cost to activity	\$306,500	First year
Expected life	15	Yrs
Time for unit construction	6	Months
Life Cycle Costs = (\$8.5k+\$250k+\$26k+\$5+\$13k/yr*15yrs+\$8k)=\$492,500		

5.1.3 Cost Analysis

Costs of the NAD may be compared, indirectly, to those for the Jet Engine Test Cell (JETC). The cost comparison must be indirect as the needs addressed by the two are somewhat different. JETCs are large buildings in which the engines are completely enclosed and the engines are tested to maximum power. The noise is reduced by 40 + dB, and the JETCs are very expensive to build (\$12M). The NAD reduces the noise produced by 20 + dB, but costs \$250k. Therefore the two, generally, have different applications although in some cases the applications may overlap. But wherever a NAD can be used in place of a JETC to reduce noise levels, the cost savings are great. This cost savings may apply: (a) at locations where noise suppression is needed but funds are not available for constructing JETCs – i.e., test stands or engine run-up pads, (b) as a potential replacement for an aging JETC, (c) as an adjunct technology for aging or newly-designed test cells. That is, the NAD should not be considered as a device in competition with the JETC, but as an inexpensive alternative technology to meet noise reduction objectives when a JETC is not feasible. It offers the advantages of being portable, inexpensive, and easily and quickly constructed and installed.

For comparison, the estimated costs for the JETC are shown in Table 5.2. These include costs for: startup/site assessment, environmental assessment, permit costs/updates for facility, equipment purchase and installation, training of operators, operation and maintenance.

Table 5.2 JETC Activity Costs

JETC Activity Costs		
Startup/Site assessment - 2 NAVFAC ESC employees - 3 days on travel	\$8,500	
Environmental assessment - 8 months NAVFAC ESC work	\$140,000	
Permit costs - could be absorbed in EA cost	\$10,000	
Equipment purchase - Per PI	\$12,000,000	
Equipment installation	\$100,000	
Training - 1 NAVFAC ESC employee 3 days travel - 3 local employees 1 day training	\$5,000	
Operation and Maintenance	\$500,000	year
Replacement Costs	\$12,100,000	per item
Disposal - Building demolition	\$150,000	One time end of life
Overall cost to activity	\$13,063,500	First year
Expected life	15	yrs
Time for unit construction	2	yrs
Environmental documentation	EA	
Time for environmental permitting	1.5	yrs
Life cycle Cost =(\$8.5k+\$40k+\$10k+\$12M+\$100k+\$5k+\$500k/yr*15yrs+\$150k)=\$ 19,813,500		

5.1.4 Life-Cycle Costs

Life-cycle costs (LCC) for the NAD were calculated assuming that its service life matched that of the JETC (the life-time used by planners of the JETC is 15 years). Elements of the LCC considered for the NAD were (see Table 5.1): startup and site assessment, design and purchase costs, installation, training, maintenance, and disposal, the latter would involve guaranteeing it was not a hazardous waste. The LCC for the NAD were determined to be \$493.k.

The LCC for the NAD may be compared to that for the JETC. The latter included costs incurred due to (see Table 5.2): site inspection, appropriate NEPA documentation, regular inspections, permitting updates, building operation and maintenance, and eventually demolition. The LCC for JETC are \$19.8 M.

5.2 Regulatory Issues

Although there does not currently exist any comprehensive EPA or other national noise regulatory standard controlling noise emissions, the increasing effect and awareness of noise in the environment (especially that due to aircraft) is leading to on-going investigations and studies that are expected to eventually lead to the enactment of some such standards. In the meantime, the standards that exist are those affecting individuals (e.g., those standards imposed by OSHA on the maximum workplace noise that workers can be exposed to) and local rules that may apply within states and /or local jurisdictions. The impact of excess noise on the local populace drives the latter. Therefore the regulatory issues that the DoD must contend with in regard to noise

from its aircraft are largely of a local nature. But the DoD must keep an eye on other regulations (federal or local) that can be anticipated, and what the DoD can do to minimize the impact of such new regulations on its operations.

5.3 Potential End-Users

The plan for transition of the NAD to DoD implementation is underway. Full-scale tests have been completed with both the non-after-burning J-52 engine and the after-burning F-404 engine at a Navy test site with Navy funding. An ESTCP project is already underway to demonstrate the NAD with the F-414 engine at NAWC PR. Successful demonstration of the NAD at this central NAVAIR test facility is key to NAD implementation at other Navy sites. Discussions have also been held with hush-house personnel at the Warner Robins AFB (WR-ALC) regarding testing the NAD with the F-100 engine (F-15 aircraft), at Tinker AFB regarding a variety of other Air Force aircraft, and with JSF program personnel regarding its possible application to the F-135 engine, a larger low-bypass engine which may require a larger version of the NAD. Potential application of the NAD to these several engines will be explored and summarized in a planned ESTCP “white paper” planned for justifying the further test / evaluation of the NAD. The range of DoD engines to which the NAD could be applicable is summarized in Table 1.1.

The best places to make connections with people involved and interested in the NAD technology are specialized meetings and workshops where the technical requirements of aircraft noise reduction are being discussed. The DoD’s Propulsion Environmental Working Group (PEWG) attracts an international audience addressing these issues, and the ONR and the AF sometimes host meetings devoted to specialized subjects such as this. A presentation on the NAD was made at the January 2005 PEWG meeting, and further contacts were made at the 2007 PEWG meeting resulting in one completed visit to Tinker AFB and other planned visits (to Tinker and elsewhere). There is also interest by NATO personnel involved in the reduction of noise from US military aircraft stationed in Europe, and the potential application of the NAD to them is still being evaluated in discussions with the chairman of that NATO noise committee. These contacts will be continued as well as developing additional ones within the DoD with personnel responsible for aircraft noise control.

The NAD can also be used for engine test purposes for which enclosed facilities (e.g., JETCs) are not applicable (i.e., where the environment of an outdoor test stand is required). Being transportable, the NAD can be easily transported to alternative locations if it is no longer needed at one, to facilitate test stand and aircraft engine run-up operations.

The performance of the NAD, per se, is not affected by weather conditions; i.e., weather should not affect the amount of noise attenuation provided by the NAD. However, weather may affect when one can use the NAD if it becomes too cold or wet for personnel to be working outside for operation of the engine. Strong winds, especially towards the engine from the direction of the exhaust, can make it undesirable to use the NAD because of the possible recirculation of exhaust gases back to the engine inlet. But the latter is a limitation that must also be considered in the testing of jet engines in enclosed JETCs.

6.0 CONCLUSIONS

The NAD has one additional milestone to complete to meet all of its stated objectives: show that it is applicable to the F-414 engine operating at A/B conditions. However, meeting that milestone seems to be just a matter of time and circumstance as testing the NAD with the F-404 engine provided conditions very close to those expected for the F-414 engine. However, the F-414 engine test remains important to demonstrate to cognizant NAVAIR personnel that the NAD can be qualified, specifically, for use with the F-414. The NAD has (a) reduced engine noise by 20 dBA; (b) shown itself to be robust and reliable at after-burner conditions; (c) shown itself to be highly transportable, although large and unwieldy; (d) a simple, inexpensive, design with almost no operating cost; and (e) a low capital cost.

Further improvements in the NAD may increase its effectiveness in reducing jet noise and make it applicable to larger as well as other types of DoD jet engines.

7.0 REFERENCES

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3. Shaver, Don and Norman Helgeson,, "Keeping The Noise at Bay," Navy CURRENTS Environmental Magazine, Spring 2005, p 26 – 33.
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APPENDIX A

Test Procedures for Testing NAD with DoD Low-By-Pass Jet Engines

Background

The below description of test procedures is based upon those used for tests with the F-404 engine.

The Noise Attenuation Device (NAD) is a static device, resembling a large scale automotive flow muffler, designed to reduce the noise generated by large, gas turbine engines under test. It was designed and developed by NAVFAC ESC, Port Hueneme CA as a Strategic Environmental Research and Development Program initiative. The NAD consists of a 6 foot diameter tube, approximately 55 ft. long with a nine ft. diameter tube surrounding the aft end of the six ft. tube. The aft end of the six ft. tube has a number of holes exiting into the space between the six and nine ft. tubes. On the internal circumference at the aft end of the six ft. tube is a flange onto which one of three end caps can be attached. One end cap consists of a series of horizontal members intended to partially interfere with the exhaust stream, the second includes two flat plates attached to the first end cap to further restrict air flow, and the third is a cone designed to even more severely block the exhaust of the engine under test and create a backpressure forcing part or most of the exhaust gases through the circular holes in the six ft. tube. The exiting air flow is then forced to exit to the forward or aft ends of the nine ft. tube.

In October 2004, a “proof of concept” test was conducted at NAWC Patuxent River’s Open-air Engine Test Facility. A J52 engine was run with and without the NAD in place to compare near- and far-field noise differences. Noise measurements were taken with each of three NAD end caps installed. Results from that test were encouraging, and prompted further funding of NAD testing. Although the NAD substantially reduced noise levels with the J52 engine, there was also evidence of exhaust gas re-ingestion at high engine power. The NAD was then modified with the addition of a deflector shield at the forward end of the outer tube. This deflector was designed to deflect exhaust gases back toward the aft end of the NAD. This design change was intended to correct the re-ingestion problem discovered in the proof-of-concept tests with the J-52 engine.

Purpose and Scope

The purpose of this test was to determine the noise attenuation of the NAD with the flow deflector installed when used with the F-404 engine. Near- and far-field noise measurements were made while the F-404 engine was running both with and without the NAD in place. Near-field measurements were taken by personnel from NAVFAC ESC. Far-field measurements were taken by representatives of the Patuxent River Office of Environmental Planning (OEP and by Maryland state representatives) at several remote locations. The most prominent of these was the Solomons Island site. The results of this test were to be used to help determine future applications of the NAD to the F-404, F-414, and other DoD jet engines.

The test was conducted to obtain the data required for noise attenuation determinations. In addition to noise reduction measurements, engine parameters were monitored to determine the influence of the NAD on engine performance.

A.1 Test Sequence

Tests were accomplished in four phases. The first phase was a baseline run of the test engine to monitor engine parameters. This will be a standard engine run without the NAD. Preliminary noise measurements were made, but this test was, primarily, for engine check-out. The second phase was a series of engine runs at increasing power settings to verify the integrity of the NAD and its instrumentation. This was also a time for test personnel to verify the performance of their recording equipment. The third phase will follow successful completion of Phase II tests, and was the official noise data runs with the NAD installed. Test points up to and including military power were run (military is the standard power against which engine power is measured and represents maximum engine power, except for the use of after-burner). The J-52 engine had no after-burner capability. Tests extending to maximum A/B power were included for the F-404 engine. Phase IV was a series of engine runs at the same engine power settings as Phase III, but without the NAD in place.

Phase I Test Sequence (Engine Check-Out):

The test sequence was as follows:

1. Start and run engine at idle for approx. 15 minutes
2. Advance engine power to 80% for approx. 15 minutes
3. Advance engine power to IRP (military power) for approx. 15 minutes
4. Advance engine power to min A/B for max 5 minutes
5. Return to idle for NAD inspection
6. Advance engine power to max A/B for max 5 minutes.
7. Shut down and inspect engine.
8. End of Phase I test.

Phase II Test Sequence (NAD Check-Out):

1. Conduct a thorough FOD check – vacuum NAD / water wash run pad from engine inlet area to the forward end of the outer NAD tube,
2. Position safety watches on each side of the engine to monitor the engine, engine cables & harnesses, test instrumentation, and NAD.
3. Start and run engine at Idle for 10 minutes.
4. Shut down engine and inspect run trailer / engine / NAD for any abnormalities such as loosening hardware, instrumentation problems, NAD tie downs and anchor bolts loosening, etc.
5. Start and run engine at 80% for 10 minutes.
6. Return to Idle and repeat inspection (step 4)
7. Start and run engine at IRP for 10 minutes.
8. Shut down and repeat inspection (step 4).
9. End of Phase II test.

NOTES:

1. At any point throughout the test, the operator will return to idle or shut-down the engine as he deems necessary, or if signaled by a safety observer.
2. Testing will cease upon any evidence of abnormalities of engine performance, the condition of the NAD or its instrumentation, or the condition of the engine SE or dress gear. At that time the test crew will assess the situation and make a determination if and how to proceed.

Phase III tests (NAD Noise Data Run):

Upon successful completion of Phase II tests, tests to acquire noise data with the NAD in place were conducted. Near-field and far-field data gatherers were positioned IAW their respective test plans. A NAVAIR representative was positioned in the OETF office building to coordinate the far-field noise data gathering team. The test cell crew alerted that representative when ready to start each test and at the time of each change in engine power setting.

The F-404 engine was run at idle, 80% IRP and IRP (military) for intervals long enough to allow for a complete set of noise data to be recorded (approx. 15 minutes). The engine was then run at minimum A/B for a maximum of five minutes. After the minimum A/B run, the engine was returned to idle for an inspection of the NAD. If all looked satisfactory, the engine was run at max A/B for a maximum of five minutes.

NOTE: It was understood that any engine performance influence of the NAD, for example re-ingestion of exhaust gases or significant performance change, could limit the power settings to be run or cause the test to be aborted.

Phase III Test Sequence:

1. Start and run engine at idle for approx. 15 minutes
2. Advance engine power to 80% for approx. 15 minutes
3. Advance engine power to IRP for approx. 15 minutes
4. Return to idle for NAD inspection
5. Advance engine power to min A/B for max 5 minutes.
6. Shut down and inspect engine and NAD
7. Advance engine power to max A/B for max 5 minutes
8. Return to idle and shut engine down.
9. End of Phase III test.

Phase IV Tests (Noise data Run W/O NAD):

Phase IV tests were a repeat of Phase III but without the NAD in place. Upon successful completion of noise gathering engine runs for Phase III, Phase IV tests commenced. The NAD was removed, and baseline noise runs were repeated at Idle, 80% IRP, and IRP followed by tests at min A/B and max A/B, as described for Phase III.

Responsibilities:**Propulsion Support Equipment T&E Personnel (4.8.6.11) responsibilities:**

- a. coordinate with Public Works to have heavy equipment and personnel to move the NAD into place for Phase II tests and to move it out of the engine run area for the Phase IV tests;
- b. operate the test cell and run the F-414 engine;
- c. control personnel access to the OETF during engine runs;
- d. coordinate with the NAVAIR Range Sustainability / NAVFAC ESC to ensure that noise measurement personnel are ready for data collection at near- and far-field sites before initiating engine runs.

NAVAIR Range Sustainability Office (5.2) responsibilities:

- a. coordinate with NAVFAC ESC in the selection of far-field noise measurement test sites; provide additional far-field test site personnel, as needed;
- b. communicate with community regarding noise tests;
- c. communicate with far-field noise monitoring teams during testing.

NAVFAC ESC responsibilities:

- a. Coordinate NAVFAC ESC and NSWDD personnel to provide the necessary equipment and personnel for making near- and far-field noise measurements; outline noise measurement and data reduction procedures;
- b. Work with NAVAIR Range Sustainability Office to select far-field noise measurement sites; select near-field noise measurement sites;
- c. Interact with Propulsion Support Equipment T&E personnel to set engine test schedules and to acquire engine operating data important to evaluation of NAD performance;
- d. During testing, coordinate engine operation with NAVAIR Range Sustainability Office personnel and near- and far-field noise measurement teams ;
- e. Ensure proper assembly and installation of the NAD;
- f. Collate and analyze noise and engine operating data;
- g. Write and distribute a final report of findings.

A.2 Jet Engine Run Procedures

The engine run procedures were in accordance with established NAVAIR procedures for running the J-52 and F-404 engines at the OETF.

A.3 Near- and Far-Field Noise Monitoring Procedures

A.3.1 Near-Field Noise Monitoring Procedures

1. Near-Field monitoring employed three handheld noise monitoring meters with 1/2inch microphones (Bruel & Kjaer 2260, Observer) and one DAT recording unit with two 1/8inch microphones at two locations. Meters with the 1/2inch microphones have a maximum recording limit of 150dbA and a recording range of 70 – 150 dbA. The 1/8 inch microphones have a maximum recording limit of 170dbA with a range of 80 – 170 dBA.
2. All microphones were placed at the top of extension poles, raising the microphones 18ft above ground level. The poles were supported by tripods. The meters were elevated to avoid noise shadows from a variety of structures and equipment present at the test site. The microphones were placed at locations that were 90 ft and 180 ft away from the Noise Attenuation Device (NAD). Microphones at 90ft from the NAD were stationary and supported on ground level with the NAD. The microphones at 180 ft from the NAD were placed at one of ten different locations that traversed a 14 ft high dirt berm. This berm added between 0 to 14ft additional height to these microphones, depending on the microphone location. However, all microphones maintained a direct line-of-sight with the center of noise production at the common distance of 180 feet from the exhaust plume. A photographic overview of the test site and a schematic layout of the meter locations were shown on Figures 3.3 and 3.7.
3. All meter clocks were synchronized.
4. All meters were certified prior to going to the field and were calibrated at the beginning and end of each day of testing.
5. Geometric locations at which sound measurements were made included locations spaced 10° apart along an arc with a 180 foot radius plus one additional location at 90 feet from the NAD (see Figure 3.7). Both the arc and the 90 ft location were measured from the center of noise production of the jet engine exhaust plume, which is estimated to be 15 feet from the exhaust plane of the engine. When facing the intake of the NAD, the location at which the NAD axis intersects the 180 ft arc was designated as the 180° measurement location. Additional measurements locations were laid out on that 180 ft arc, proceeding to the left, to locations at 170°, 160°, 150°, 140°, 130°, 127°, 120°, 110° and 100°. The 90 ft location is on the 127° radii.
6. One 1/8inch microphone was placed at the 90 ft - 127° location and also at the 180ft - 127° location. These meters remained in the recording mode throughout each block of testing.
7. One 1/2inch microphone, referred to as the “roving meter,” was used to make measurements of 15 seconds duration at each of the ten locations (from 100° to 180°) along the 180ft arc for each power setting of the jet engine. The roving meter began measurements once the jet engine had reached a prescribed run operating condition.
8. During roving meter measurements the noise meter reading was recorded in a hand-written log for each location at each test condition.
9. All data recorded electronically was stored either in the internal memory of the meter or on the DAT recorder tape until the end of each day of testing.

10. The data recorded on the DAT recorder was maintained on the recorded tape. A new DAT recorder tape was used at the beginning of each day of testing. This data was then secured for transport to the office for analysis. The data was later archived on CDs.
11. The data stored on the meter memories was transferred to the hard drive of a laptop computer at the end of each day. A duplicate copy of the data was also transferred to a “thumb” drive. This data was then secured for transport to the office for analysis. The data was later archived on CDs.

A.3.2 Far-Field Noise Monitoring Procedures

1. NAVAIR personnel were instructed in the operation of the sound level meters selected to collect sound data.
2. Sound level meters (SLM) with valid calibration stickers were supplied to personnel designated to collect data.
3. SLM were configured in accordance with paragraph B.2, Appendix B.
4. The SLM were acoustically calibrated and the time set to GPS timing.
5. Monitoring personnel were then sent to their respective monitoring sites.
6. The geographic location in latitude and longitude of the monitoring site was recorded.
7. The SLMs were turned on and placed in the record mode 10 minutes prior to engine operation to provide a baseline.
8. SLMs continued to record data for the duration of each test phase and continued recording for 10 minutes after the engine was shut down.
9. The SLMs were returned to the QC officer who completed acoustical calibrations compared post-test calibration factors to the pretest values.
10. The data were downloaded to a laptop computer.

A.3.3 Health and Safety Procedures

Personnel shall comply with the Propulsion Support Equipment Safety Checklist and the standard Ground Checklist (see Tables C.1 and C.2, Appendix C). Additionally, all personnel will remain well clear of the area around the entrance of the NAD. This bellmouth area could present a dangerous situation because of the high air flow rate entering the NAD.

Any person discovering a fire or life threatening emergency shall pass the word to all hands as quickly as possible and report it without delay by activating the nearest pull station and dialing 342-3911.

All fires (even those handled without damage or injury) will be reported. Safety watches will ensure no unauthorized people wander into the test area, and if so the safety watches will notify the operator to shut down the engine.

A safety brief will be held on site just prior to beginning tests. All personnel participating in the test event will be present for the brief.

APPENDIX B

Analytical Methods Supporting the Experimental Design

Analytical and monitoring methods for reporting data describing engine operations and noise measurements are as follows.

B.1 F-414 Engine Data Reduction Procedures

Engine data reduction procedures will be in accordance with those established by NAVAIR for the F-414 engine running at the OETF.

B.2 Sound Level Measurement Standards and Procedures will conform with the following specifications:

- IEC60651 (1979) Specification for Sound Level Meters ,Type 1 plus Amendments 1 and 2
- IEC60804 (2000) Type 1
- IEC61672 (Draft March 2001) Class 1
- IEC61260 (1995) Octave Bands and 1/3-octave Bands Class 0

B.2.1 United States Specifications

- ANSI S1.4-1983 Specification for Sound Level Meters Type 1 plus ANSI S1.4A–1985 Amendment
- ANSI S1.43-1997 Specifications for Integrating-Averaging Sound Level Meters, Type 1
- ANSI S1.11-1986 Specifications for Octave-Band and Fractional Octave-Band Analog and Digital Filters, Order 3, Type 0-C, Optional Range

B.2.2 Sound Level Meter Calibration

- ISO/IEC 17025:2005 General requirements for the competence of testing and calibration laboratories
- ISO 10012:2003 Measurement management systems -- Requirements for measurement processes and measuring equipment
- ANSI/NCSL Z540-1(1994) Calibration Laboratories and Measuring and Test Equipment - General Requirements-Replaces Mil-Std-45662

B.2.3 Data Analysis Software

- ISO1996-2 Acoustics -- Description, measurement and assessment of environmental noise -- Part 2: Determination of environmental noise levels
 - NCSL -National Conference of Standards Laboratories
 - ISO- International Standards Organization
 - IEC- The International Electrotechnical Commission
 - ANSI- American National Standards Institute

APPENDIX C

Health and Safety Plan

The following safety checklists for testing with the J-52 and F-404 engines were based upon the standard operating procedures of OETF at the Patuxent River NAS.

Table C-1: Propulsion Support Equipment Safety Checklist

1. The test operator on the throttle must be completely familiar with all safety and emergency procedures related to the system and engine being operated. The project engineer is responsible for ensuring that all personnel in the test area comply with proper safety procedures and have been properly briefed.
2. If unfamiliar with test cell/system operations, project personnel are responsible for getting briefed on the particular systems/engines.
3. Test cell/system crew is responsible for ensuring that adequate firefighting equipment is at the test site at all times.
4. All members of the test cell/system crew must know how to operate installed test system fire extinguishing systems.
5. Any person discovering a fire or life threatening emergency shall pass the words to all hands as quickly as possible and report it without delay by activating the nearest pull station and dialing 342-3911. All fires (even those handled without damage or injury) will be reported.
6. No one will operate the test cell/systems and ancillary equipment unless fully qualified.
7. Everyone will use proper sound protection devices when operating test cell/systems and ancillary equipment.
8. Utilize eye protection when appropriate.
9. Test cell/system crew is responsible for making certain the area is clear of foreign objects.
10. Test cell/system crew is responsible for immediate clean up of all fluid spills in test area; i.e., fuel, oil, and hydraulic fluid.
11. Avoid engine intake areas.
12. Avoid engine exhaust areas.
13. Avoid the engine plane of rotation areas.

14. On turbo shaft test systems, avoid the air dynamometer rotor plane of rotation area and dynamometer exhaust areas.
15. Ensure that a safety observer is stationed outside by the engine run trailer when operating unenclosed test systems.
16. Ensure that continuous communications are maintained between the test system operator and the safety observer.
17. All personnel inform the engine operator of your movements and intentions around a running engine.
18. Do not enter an enclosed engine run chamber except when the engine is at "idle".
19. Do not drive or push mobile equipment over test system interconnecting lines or cables (fuel, oil, hydraulic, electrical, and air).
20. Make certain no ground support equipment is unsecured especially when operating turboprop engines.
21. Exercise caution when working on test system pneumatic systems.
22. Exercise caution when handling fuels, oils, and hydraulic fluid.
23. Ensure adequate lighting is available at the test site during night tests.

Table C.2 GROUND TEST SAFETY CHECKLIST for NAD Tests

1. PURPOSE: This checklist is to stimulate thought in the area of safety. Most of these questions have been written from lessons learned from past accidents in the RDT&E community.

CHECKLIST

- A. What test procedures are being followed (SOP, Test Plan, etc.)?
Tests will be conducted in accordance with engine and test procedures included in the demonstration plan.
- B. If aircraft are being used for this test, list the safety-related discrepancies, which are applicable to the aircraft systems to be used/tested? If test is to be performed at EWISTL, the Hero Pad or Shielded Hangar, will ensure all equipment to be used is operational prior to the test.

N/A

- C. What background material from similar/previous tests has been reviewed, and known problems areas studied: Have other agencies, both military and civilian, who have been known to conduct similar tests, been consulted so that benefit can be realized from the consideration of their standard procedures and lessons learned? If the ground test involves modified or new equipment similar to in- service equipment, are there technical publications that can be used as a guideline?

Similar tests were conducted with the J-52 and F-404 engines with many of the same personnel involved. The J-52 engine had no after-burner; the F-404 engine had an A/B. The F-404 was run at successively higher power settings up to, and including, Max A/B, without incident. Problems previously identified include loosening of NAD hardware and exhaust gas recirculation and ingestion into the engine. The NAD hardware has been changed to include lock washers to minimize the likelihood of the hardware loosening, and an exhaust gas deflector has been added to the outer circumference of the NAD to reduce the likelihood of exhaust gas re-ingestion. No re-ingestion was observed during testing with the F-404 engine. Safety observers watched for loosening hardware throughout the tests, and test cell personnel closely monitored engine parameters.

- D. What pre-test checks of a safety nature will be conducted to assess proper operation of the project and emergency equipment unique to the test?

The NAD will be vacuumed and the run pad will be washed down with water to minimize FOD hazards. All hardware will be inspected for integrity.

- E. In order to ensure that no undue hazard to ground personnel or possible damage to equipment exists, what changes or special precautions to normal aircraft maintenance and/or ground handling procedures are required?

One or possibly two people will be required to stand in a very high noise environment during engine runs to collect noise measurement data. There could also be gusty winds created by the engine exhaust. Double hearing protection and eye protection will be required. This will include a cranial with goggles and foam inserts.

- F. If locally manufactured components are necessary for the completion of the project, what steps have been taken to ensure that adequate detailed drawings/schematics and operating instructions are prepared, components inspected and tested prior to installation in accordance with current quality assurance/configuration control instructions? What safety precautions are necessary for locally manufactured components?

N/A

- G. Does the test instrumentation system under any condition prevent normal operations of aircraft systems/support systems? If so, describe.

N/A

- H. Engineering design deficiencies are not uncommon in project equipment; therefore, a hazard analysis and risk assessment is required so that we can systematically determine possible hazards and minimize surprises.

(1) What system and subsystem failures would create hazards for this test? What analysis was done to ensure the safety of special mechanical and/or electrical systems being used?

Hardware failures such as loose nuts or bolts could create a FOD hazard. Hardware will have retaining devices (lock washers), and safety observers will be stationed to watch the hardware during engine runs and inspect it between runs.

(2) If the failures cannot be eliminated, what special precautions, emergency procedure are anticipated?

One of the safety observers is positioned in direct sight of the test cell operator and is designated as the primary safety observer. If any of the safety observers, some of whom cannot be seen by the test cell operator, detect any condition that might present a safety hazard to equipment or personnel, they will signal the primary observer. The primary observer will then signal the operator to throttle back to idle or to shut down the engine as conditions warrant.

(3) If any safety device or interlock will be bypassed or overridden in these tests, what additional hazards are involved and what steps will be taken to reduce these risks?

N/A

- I. Is there a prescribed safe distance for bystanders, test conductors, and technicians? What protective equipment shall be used by personnel inside this perimeter?

All personnel in the engine run area at the OETF will be required to wear hearing protection.

- J. Have appropriate project personnel received briefings on the ejection seat and emergency systems, as applicable?

N/A

- K. Have appropriate project personnel been briefed on proper settings of switches and circuit breakers applicable to safe ground operation of the aircraft under test?

N/A

- L. What precautions have been taken to prevent exposure of personnel to hazardous electromagnetic radiation?

N/A